# TURN-TO-TURN FAULT DETECTION IN TRANSFORMERS USING NEGATIVE SEQUENCE CURRENTS

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by

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# ABSTRACT

A power transformer is one of the most important and expensive components in any power system. Power transformers can be exposed to a wide variety of abnormal conditions and faults. Internal turn-to-turn faults are the most difficult types of faults to detect within the power transformer. The IEEE Standards documents have revealed that there is no one standard way to protect all power transformers against minor internal faults such as turn-to-turn faults and at the same time to satisfy basic protection requirements: sensitivity, selectivity, and speed.

This thesis presents a new, simple and efficient protection technique which is based on negative sequence currents. Using this protection technique, it is possible to detect minor internal turn-to-turn faults in power transformers. Also, it can differentiate between internal and external faults. The discrimination is achieved by comparing the phase shift between two phasors of total negative sequence current. The new protection technique is being studied via an extensive simulation study using PSCAD®/EMTDC™ [1] software in a three-phase power system and is also being compared with a traditional differential algorithm.

Relay performance under different numbers of shorted turns of the power transformer, different connections of the transformer, different values of the fault resistances, and different values of the system parameters was investigated. The results indicate that the new technique can provide a fast and sensitive approach for identifying minor internal turn-to-turn faults in power transformers.


[1] PSCAD®/EMTDC™ : Trademark of the Manitoba HVDC Research Centre.

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# *DEDICATION*

*This thesis is dedicated to my parents, Oksana and Mykhailo, who have raised me to be the person who I am now. Also, this thesis is dedicated to Donald Robinson, who believed in me, inspired me and has supported me all the way from the beginning of my graduate studies.*

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# LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| IEEE | The Institute of Electrical and Electronics Engineers |
| PSCAD | Power Systems Computer Aided Design |
| EMTDC | The Electromagnetic Transient Program |
| DC | Direct current |
| AC | Alternating current |
| HV | High voltage |
| LV | Low voltage |
| *kVA* | Kilo Volt Ampere |
| *MVA* | Mega Volt Ampere |
| $f$ | Frequency |
| Hz | Hertz |
| $i_o$ | Excitation current |
| $\Phi$ | The mutual flux in the transformer’s core |
| $V_p$ | The primary voltage of the transformer |
| $E_p$ | The voltage at the primary terminal of the transformer |
| $V_s$ | The secondary voltage of the transformer |
| $N_p$ | The number of turns in the primary coil of the transformer |
| $N_s$ | The number of turns in the secondary coil of the transformer |
| $\Phi_{max}$ | The maximum value of the flux |
| ω | Angular frequency |
| RMS | Root mean square |
| $I_p$ | The primary current |
| $I_s$ | The secondary current |
| $N_x$ | Number of shorted turns |
| $I_x$ | The additional current component caused by the induced voltage in the short circuited turns |
| CT | Current transformer |

| | |
|---|---|
| RC | Restraining coil |
| OP | Operating coil |
| DWT | Discrete wavelet transform |
| ANN | Artificial neural network |
| $I_a$ | Current of phase A |
| $I_b$ | Current of phase B |
| $I_c$ | Current of phase C |
| $I_1$ | Positive sequence current |
| $I_2$ | Negative sequence current |
| $I_0$ | Zero sequence current |
| $I_N$ | Neutral current |
| $a$ | phasor operator equal to 120 degree |
| $A^{-1}$ | The inverse matrix |
| $Z_1$ | Positive sequence impedance |
| $Z_2$ | Negative sequence impedance |
| $Z_0$ | Zero sequence impedance |
| $Z_f$ | Fault impedance |
| $Z_l$ | Leakage impedance |
| $V_f$ | The pre fault voltage |
| $Z_a$ | Impedance of phase A |
| $Z_b$ | Impedance of phase B |
| TR | Transformer |
| $Z_{NS\_S1}$, $Z_{NS\_S2}$ | The negative sequence impedances for the equivalent sources $S_1$ and $S_2$ |
| $E_{NS}$ | Fictitious negative sequence source |
| *INS_P*, *INS_S* | The negative sequence currents on the primary and secondary side of TR |
| *INS_P'* | The negative sequence current transformed from the fault side to the other side of TR |
| $I_{NS\_P}$ , $I_{NS\_S}$ | The negative sequence currents on the primary and secondary side of TR scaled down using CTs |
| FFT | Fast Fourier Transform |

| | |
|---|---|
| $I_{min}$ | The minimum pre-set level |
| $S_1$,$S_2$ | Voltage sources |
| BRK | Circuit breaker |
| $V$ | Line-to-ground, peak voltage magnitude |
| $S$ | The maximum load |
| $L_1$ | self-inductance in the primary winding |
| $L_a$, $L_b$, $L_c$ | self-inductance of sub coils “a”, “b” and “c” |
| $M_{1a}$ , $M_{1b}$, $M_{1c}$ | mutual inductance between primary winding and sub coils “a”, “b” and “c” |
| $M_{ab}$ , $M_{ac}$, $M_{bc}$ | mutual inductance between sub coils “a”, “b” and “c” |
| $N$ | Number of turns of the winding |
| $l$ | The mean length of the magnetic circuit |
| $\mu_0$ | The permeability |
| $A_g$ | Cross-sectional area of core |
| $L$ | Inductance |
| $I_d$ | Differential current |
| $K$ | Compensation factor |
| $I_r$ | Restraint current |
| *SLP* | The slope of the percentage differential characteristic |
| *TTC* | Transformer tap changing |
| $M$ | The percentage of the current’s mismatch |
| $I_L$, $I_H$ | Relay input currents at the same kVA base for low and high voltage sides respectively |
| $T_L$, $T_H$ | Relay tap settings for low and high voltage sides respectively |
| *Mag+* | Positive sequence magnitude component |
| *Mag-* | Negative sequence magnitude component |
| *Mag0* | Zero sequence magnitude component |
| *Ph+* | Positive sequence phase component |
| *Ph-* | Negative sequence phase component |
| *Ph0* | Zero sequence phase component |

| | |
|---|---|
| $I_{A1}$, $I_{B1}$, $I_{C1}$ | Phase currents on the primary side of the power transformer in phase A, B, and C respectively |
| $I_{A2}$, $I_{B2}$, $I_{C2}$ | Phase currents on the secondary side of the power transformer in phase A, B, and C respectively |
| $I_{SA1}$, $I_{SB1}$, $I_{SC1}$ | Secondary phase currents produced by CT's on the primary side of the power transformer in phase A, B, and C respectively |
| $I_{SA2}$, $I_{SB2}$, $I_{SC2}$ | Secondary phase currents produced by CT's on the secondary side of the power transformer in phase A, B, and C respectively |
| $I_{NS\_P\_ph}$ | Phase angle of the negative sequence current on the primary side of TR is output from FFT block |
| $I_{NS\_S\_ph}$ | Phase angle of the negative sequence current on the secondary side of TR is output from FFT block |
| LCUR | Line current unbalance ratio |
| RTDS ™ [2] | Real Time Digital Simulator |

[2] Registered trademark of RTDS Technologies, Winnipeg, Canada.

# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction to the power transformer

One of the most important and complex systems that has been built by human civilization is the power system. The electric power system plays a key role in modern society. One of the most important components of any power system is the power transformer.

The development of the first power transformer significantly changed transmission and distribution systems. Before the power transformer was invented in 1885 by William Stanley, power was produced and distributed as direct current (DC) at low voltage. The use of electricity was only limited to urban areas because of voltage drop in the lines. Also, the use of DC voltage would require the supply voltage to be the same as the supply voltage required by all electrical equipment connected to the power system. However, it is quite difficult to transform DC power to a lower current and high-voltage form efficiently. The alternating current (AC) system is able to overcome the limitation of the DC system and distributes electricity efficiently over long distances to consumers. The use of the AC system allows the use of a multi-voltage level energy delivery system. The AC power, generated at a low voltage, can be stepped up by using the power transformer for the transmission purpose to higher voltage and lower current. Thus, voltage drops and transmission energy losses can be reduced.

The transformer is the link between the generator of the power system and the transmission lines. A power transformer is defined in reference [1] as a static piece of apparatus with two or more windings which by electromagnetic induction, transforms a system of alternating voltage and current into another system of voltage and current usually of different values and at the same frequency for the purpose of transmitting electrical power.

The power transformer makes it possible to transmit the power from the generating station to the customers at a distance. The power transformer is the most important and critical component of the power system that transfers electrical energy from one circuit to another through the power transformer's coils. Power transformers are able to transfer 99.5% of their input power as their output power.

The life-span of the power transformer is about 30 years in service. Transformers are divided into three groups [2]:

1) Small power transformers 500 – 7500 kVA.
2) Medium power transformers 7500 kVA – 100 MVA.
3) Large power transformers 100 MVA and above.

However, the power transformer can sometimes fail due to different factors. One of the major factors that can cause the power transformer to fail is increasing the power consumption. Increasing the power consumption every year leads the load on the power transformer to grow. When the load on the power transformer increases, the operating stresses increase as well. According to the report on analysis of transformer failures presented at International Association of Engineering Insurers, 36$^{th}$ Annual Conference in Stockholm in 2003 by William H. Bartley, the largest transformer loss occurred at a power plant in 2000 and the total damage loss of this power transformer was 86 million US dollars [3]. The continuity of the power transformer operation is very important in maintaining the reliability of the power supply. Any unscheduled repair work such as replacement of the faulty transformer is very expensive and time consuming.

### 1.1.1 Principles of the power transformer

The operation of a power transformer is based on two principles:

1. Electric current produces the magnetic field.

The primary winding of the transformer is connected to a source of sinusoidal voltage of frequency $f$ Hz and draws a small excitation current $i_o$ from the source. This excitation current sets up the mutual flux in the transformer's core $\Phi$.

2. A change in the magnetic field within a coil of wire induces a voltage across the ends of the coil (electromagnetic induction).

Changing the current in the primary coil changes the magnitude of the applied magnetic field. The changing magnetic flux extends to the secondary coil where a voltage is induced across its ends. Therefore, the primary and secondary windings of the transformer are not connected electrically, but magnetically [2]. Electric energy is transferred between two circuits without the use of moving parts. The ideal power transformer is depicted in Figure 1.1.

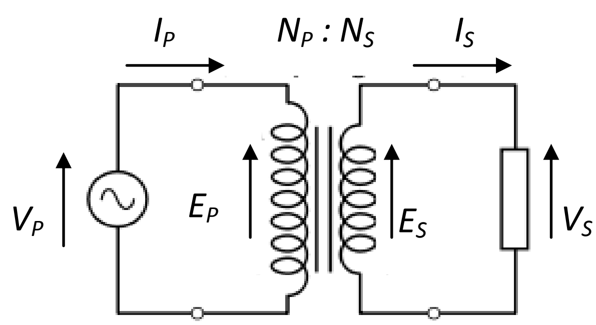



Figure 1.1 – The ideal transformer

For the ideal power transformer, it is assumed that resistance of the primary and the secondary windings equal zero. Since the resistance is zero, there is no voltage drop in the transformer winding, so the voltage at the power transformer terminals equals the induced voltage in the winding ($V_p = E_p$).

The secondary voltage $V_s$, induced in the secondary winding, is proportional to the primary voltage $V_p$, and is given by the ratio of the number of turns $N_s$ in the secondary winding to the number of turns $N_p$ in the primary winding [2]. The voltage induced in the secondary coil is:

$$V_s = N_s \frac{d\Phi}{dt} \tag{1.1}$$

Where $N_s$ - the number of turns in the secondary coil,

$\Phi$ - the magnetic flux through one turn of the coil.

The same magnetic flux passes through the primary and the secondary coils of the power transformer causing the instantaneous voltage across the primary winding to be equal to:

$$V_p = N_p \frac{d\Phi}{dt} \tag{1.2}$$

Where $N_p$ - the number of turns in the primary coil,

$\Phi$ - the magnetic flux through one turn of the coil.

The waveforms of the flux and the voltage are sinusoidal. The instantaneous value of the flux is:

$$\Phi = \Phi_{max} sin\omega t \tag{1.3}$$

Then the induced voltage is:

$$E_p = N_p \frac{d\Phi}{dt} = \omega N_p \Phi_{max} cos\omega t \tag{1.4}$$

Where $\Phi_{max}$ - the maximum value of the flux,

$\omega = 2\pi f$ - angular frequency.

The RMS value of the induced voltage is:

$$E_p = \frac{2\pi}{\sqrt{2}} f N_p \Phi_{max} = \sqrt{2}\ \pi f N_p \Phi_{max} \tag{1.5}$$

Since the voltage drop in the winding resistance is neglected and then induced voltage equals the terminal voltage. Then if a sinusoidal voltage is applied to the winding, sinusoidally varying flux has to be established with the maximum value $\Phi_{max}$ and satisfy the requirements that induced voltage equals the RMS value of the terminal voltage.

$$\Phi_{max} = \frac{V_p}{\sqrt{2}\pi f N_p} \tag{1.6}$$

As can be seen, the core flux depends on the applied voltage, the number of turns in the winding, and the frequency. The core flux is fixed by the applied voltage and also by the required exciting current which is determined by the magnetic properties of the core.

### 1.1.2 Types of transformer failures

Damages to the power transformer can be caused by different stresses, which are due to overheating, open circuits and short circuits [4]. The major focus of power transformer protection is short circuits because open circuits do not present a particular hazard. Short circuit protection includes internal and external faults.

External faults occur outside the protection zone of the transformer and include:

1. Over voltage – stresses the insulation beyond its withstand capacities and therefore causing breakdown of the transformer.
2. Overloads – lead to overheating of transformers' insulation and have the potential to cause permanent damage.
3. Under frequency – caused by a system disturbance that causes an imbalance between generation and load. The exciting current increases at low frequencies causing overfluxing of the transformer iron core. Overfluxing may gradually lead to insulation breakdown of the magnetic circuit.

Internal faults occur within the transformer protection zone. The internal faults can be divided into two groups [3] - [6]:

**1.** Incipient faults develop slowly and may develop into major faults such as phase-to-ground faults or three phase faults if the cause is not detected and corrected. Incipient faults can be divided into three groups:

- Overheating – caused by loss of coolant which is due to leakage, poor internal connection in the electric or magnetic circuits, and loss of fans which have to provide cooling.
- Over fluxing – may lead to insulation breakdown of the magnetic circuit insulating materials.
- Overpressure – occurs due to release of gases from the transformer.

**2.** Active faults – caused by the breakdown in insulation which creates a sudden stress. The active fault occurs when the current flows from one phase conductor to another such as phase-to-phase and phase-to-ground. These faults may occur suddenly and they require fast action by protective relays. Active faults:
   - Turn-to-turn short circuits.
   - Phase-to-phase short circuits.
   - Phase-to-ground short circuits.
   - Tank faults.
   - Core faults.

One of the most challenging problems in power transformer protection is detecting internal turn-to-turn faults. The reason why it is difficult to detect minor internal faults within the power transformer is explained in the following sections.

## 1.2 Transformer internal turn-to-turn faults

According to the IEEE Standard C37.91-2000, which gives failure statistics of transformers for different time periods, more than 50% of the total numbers of failures are winding failures [7]. Winding failures are due to insulation between turns which can break down due to electromagnetic and mechanical forces on the winding.

A single-phase, two winding transformer with an internal turn-to-turn fault is depicted in Figure 1.2 to explain the theory about turn-to-turn faults. A turn-to-turn short circuit is a short circuit of a few turns in the transformer windings. Figure 1.2 shows that a turn-to-turn fault has occurred in the secondary windings and involves $N_x$ turns.

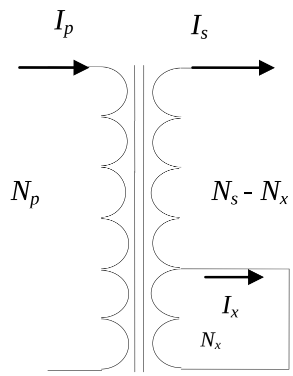



Figure 1.2 – The single-phase, two winding transformer

Where $I_p$, $I_s$ - the primary and secondary current,

$N_p$, $N_s$ - number of turns on the primary and secondary side of the power transformer,

$N_x$ - number of shorted turns.

$I_x$ is the additional current component which is caused by the induced voltage in the short circuited turns. This current component is not measured by the differential relay to circulate through the shorted turns. The additional current component will be lagging the voltage by 90 degrees because the impedance of the shorted circuit is inductive. The Ampere-turn-balance principle for the coils which are located on the same magnetic core has to be fulfilled, irrespective of the existence of a turn-to-turn fault. In order to fulfill this requirement, two measured currents will give a certain angle shift $\delta$ (Figure 1.3).

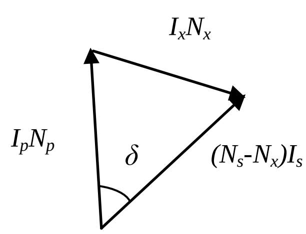



Figure 1.3 – The ampere-turn-balance principle

The component $I_x N_x$ is seen by the differential relay as the differential current. When turn-to-turn faults occur within the power transformer and only a few turns are shorted, then the differential current magnitude can be very small and might not be within the tripping region.

According to the analysis of power transformer failures, 94 power transformers failed for the period of 1997 through 2001 [3]. The total loss of 94 power transformers was $ 286,628,811 US dollars. According to the Annual Report presented at 36th Annual Conference in Stockholm in 2003, the largest numbers of transformer failures occur in the Utility Substation sector and the cause of power transformer failures is insulation failure. For all different types of power transformer failures, insulation failure has the highest risk to fail [8]. The cause of developing turn-to-turn faults is the degradation of the insulation system. The insulation system of the transformer consists of paper and oil. The paper and oil can be subject to aging, which is defined as the change in the properties of an electrical insulation system. Degradation is the process of reducing insulation quality, which causes a breakdown in the insulation and leads to development of turn-to-turn faults. The degradation of the insulation system can be due to the mechanical, electrical, and thermal stresses, and moisture. When failure of the power transformer happens, immediate detection of the failure is necessary in order to protect the entire power system and minimize the damage and repair cost. If the turn-to-turn fault has not been quickly detected and cleared, then this turn-to-turn fault can develop into a more serious and costly to repair fault such as a phase-to-ground fault.

For detecting internal turn-to-turn faults in the power transformer three characteristics can be used. These three characteristics are [9,10]:

1) Gas formation which is caused by the fault arc.
2) An increase in the phase currents.
3) An increase in the differential current.

When internal faults occur within the power transformer, immediate detection of these faults is necessary in order to protect the entire power system and minimize the damage and repair cost. Usually three types of protection can be used to protect the transformer from the internal faults:

**1. Sudden pressure relay**

The sudden pressure relay operates on a rate of rise of gas in the transformer [10] - [12]. This relay does not operate on pressure changes or static pressure which results from the normal operating condition of the transformer.

**2. Over current relay**

Over current relays are seldom used because of their vulnerability to false operation [9] - [12]. The false operation of over current relays might be caused by mismatch errors of current transformers (CT's), saturation errors, and magnetizing inrush current when the transformer is energized. The over current relay responds to the magnitude of the input current and operates when this magnitude exceeds the pre-set level – pickup current. Then the over current relay contacts will close to energize the circuit breaker trip coil. The contact of the relay will remain open if the magnitude of the input current is less than the pickup current. Over current relays are used as primary protection where differential protection is not used. If the differential protection is used, then the over current relay is used as back up protection. Typically, fuses are used as primary protection for transformers rated below 10 MVA. For transformers rated above 10 MVA, differential relays are used as primary protection and over current relays as back up.

**3. The percentage differential relay**

Differential relaying is one of the most effective and reliable methods of providing protection against internal faults in power transformers. The percentage differential relay is depicted in Figure 1.4.

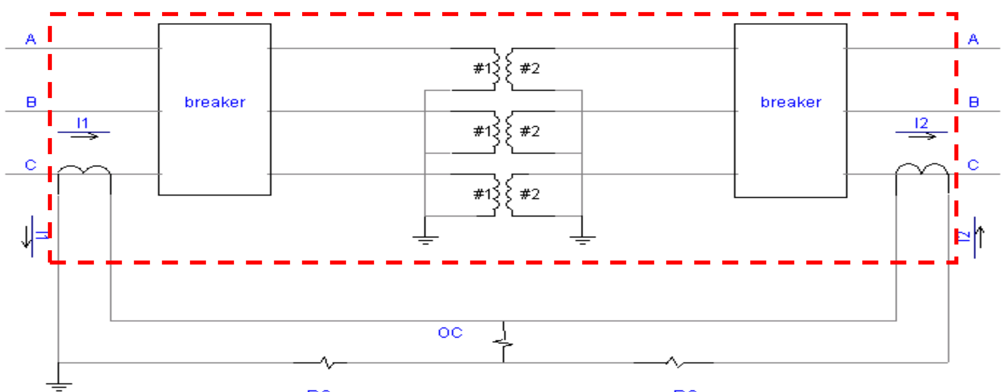



Figure 1.4 – Percentage differential relay

Differential relaying treats the power transformer as a unit, taking measurements at all of the transformer terminals. This method is very convenient because the power transformer terminals are located at the same terminal. As it can been seen from the Figure 1.4, the differential protection principle is based on comparing current magnitudes which enter ($I_1$) and leave ($I_2$) the protected zone. The protected zone is the zone between two current transformers. Under normal conditions, the current $I_1$ would be equal to the current $I_2$. Therefore, during normal system operation and during external faults (faults outside of the protection zone) the differential relay operating current is very small or near zero. If the fault occurs between the two ends of the protected zone, the magnitudes of the current $I_1$ and $I_2$ are no longer equal. Then the presence of the fault can be detected [12].

It can be observed from Figure 1.4 that the percentage differential relay has two types of coils: the restraining coil (RC) and the operating coil (OC) [9]. The percentage differential relay operates when the differential current between currents entering and leaving the protected zone exceed a pre-determined percentage of the through current before tripping can occur. This through current is referred to as the restraining current. Operation of the differential relay occurs when the operating current exceeds the restraining current.

The major component of the differential protection scheme is the current transformer (CT). The current transformer is connected in series with the power transformer windings with the secondary currents circulating between them. The relay is connected across the midpoint where the voltage is theoretically nil. Therefore, no current passes through the relay, and hence no operation for faults outside the protected zone. Under internal fault conditions the relay operates and both CT secondary currents add up and pass through the relay. The percentage differential relay can be instantaneous in operation as it does not have to coordinate with any other relay on the network.

In order to correctly apply the differential protection, two requirements have to be satisfied [13]:

1. The current magnitude differences on different sides of the protected transformer have to be compensated by correct selection of interposing CT ratios. It is necessary to properly compensate the phase shift between the windings by correct selections of interposing CT

winding connections.  Some differential relays might internally accommodate the phase shift of the transformer.

2. It is important to compensate for zero sequence current by using the interposing CT connection, which makes it possible to remove zero sequence current.

Percentage differential relays must be tolerant of worst-case addition of the mismatch errors. Percentage differential relays allow larger percentage mismatches up to 70% during heavy through currents [9].  Percentage differential relays can be affected by a number of factors, which are explained below:

**Magnetizing inrush current**

Magnetizing inrush current is the current which may flow when the transformer is first energized [14] - [15].  The inrush current may reach the instantaneous peaks of 8 to 30 times that for full-load current, and then decays rapidly during the first few cycles before decaying slowly.  The magnitude of the inrush current is affected by the following factors: type of the magnetic material in the core, residual flux in the power transformer before switching on, and the size of the power transformer.  Since the differential relay might see the inrush current as an internal fault, some methods should be present, such as a harmonic restraint, for distinguishing between faults and inrush current [16] - [17].  The inrush current has a second harmonic.  This second harmonic can be used to restraint or block a relay during energization and avoid undesired tripping.  The second harmonic blocking can respond to magnitudes and phase angles of the second harmonic and the fundamental frequency currents.  The differential element can correctly distinguish between the power transformer energization and faults.

**Transformer tap-change operation**

Transformer tap change operation makes a large contribution to current mismatch [15].  A typical load tap changer range of 10% in voltage gives a 10% variation in current.  When on load tap-changer moves from one position to another, amplitude mismatch between the transformer windings will result in a false differential current.  This is a significant mismatch for which the relay must not operate.

**Current transformer (CT) saturation**

Fault currents can lead to CT saturation [15]. Current transformer saturation might cause the relay operating current to flow due to the distortion of the saturated current. Current transformer saturation reduces the secondary output currents from the current transformer and causes a false differential current to appear to the relay. To minimize problems due to the saturation, the CT's ratios have to be selected properly.

**Over excitation**

Transformers are designed to operate below the flux saturation level [18]. An increase from the maximum voltage level will lead to saturation of the core and an increase in the excitation current drawn by the transformer. When a transformer core is over excited, the core will operate in a non-linear magnetic region. This will create harmonic components in the exciting current. There is a significant amount of current at the fifth harmonic that is characteristic of over excitation.

**30º phase angle shift introduced by transformer Y-Δ connection**.

The connection of the power transformer windings produces a phase displacement from the primary currents and voltages to the secondary currents and voltages.

Besides detecting the fault, percentage differential relay also has to be sensitive to all of the above mentioned factors which can cause misoperation of the relay.

## 1.3 Literature review

Internal faults involve a magnitude of fault current which is low relative to the power transformer base current. This indicates a need for high speed and high sensitivity to ensure good protection. According to the IEEE Standard documents, there is no one standard way to protect all power transformers against minor internal faults and at the same time to satisfy basic protection requirements: sensitivity, selectivity, and speed [7].

The most difficult internal turn-to-turn fault is the fault which initially involves only a few turns. The IEEE Standard C37.91-2000 indicates that as much as 10% of the transformer winding might be shorted to cause a detectable change in the terminal current. Therefore, when fewer numbers of turns are shorted, it will result in an undetectable amount of current. There is no limit to the maximum internal fault that can flow, other than the protection system capability [7].

According to the IEEE Committee Report [7], the main and most commonly used protection provided for internal faults for power transformers of approximately 10 MVA three-phase is the percentage differential relay. Although the percentage differential relay is the most commonly used protection, it is not thoroughly efficient for detecting minor internal turn-to-turn faults in power transformers. It is difficult to detect minor internal turn-to-turn faults using the percentage differential relay because the changes in the transformer terminal's current will be quite small because the ratio of transformation between the whole winding and the short-circuited turns is quite small. The traditional transformer differential percentage protection is not sensitive enough to detect minor internal winding faults. Low-level turn-to-turn faults cannot be detected with overall sensitivity represented by the restraint characteristic of the percentage differential relay. For example, if the restraint characteristic of the percentage differential relay has been set to 20% and a minor internal fault causes a differential current of 10%, thus an internal fault cannot be detected until this fault evolves into a more severe fault with a higher differential current. And for this reason, the conventional percentage differential protection is not sensitive enough to determine low-level turn-to-turn faults.

Alternatively, minor turn-to-turn faults can be detected by the sudden pressure relay. However, the sudden pressure relay is slow to operate unless the internal fault is severe. The sudden pressure relay can detect internal faults with a delay of typically 50-100 ms that often causes the fault to become more serious. Reference [6] gives a real case study on transformer failure due to shorted turns. Failure of transformer by shorted turns is depicted in Figure 1.5. A turn-to-turn fault was developed in a 30 year old power transformer as a result of severe winding conductor insulation aging. The power transformer was tripped on sudden pressure relay. After the fault was cleared, fault diagnosis showed extensive loss of conductors and conductor insulations in the faulted phase, which was unlikely to be economically repairable. As it can be seen from this real case study, the internal turn-to-turn fault was detected but with a time delay that caused severe damage of the faulted winding.

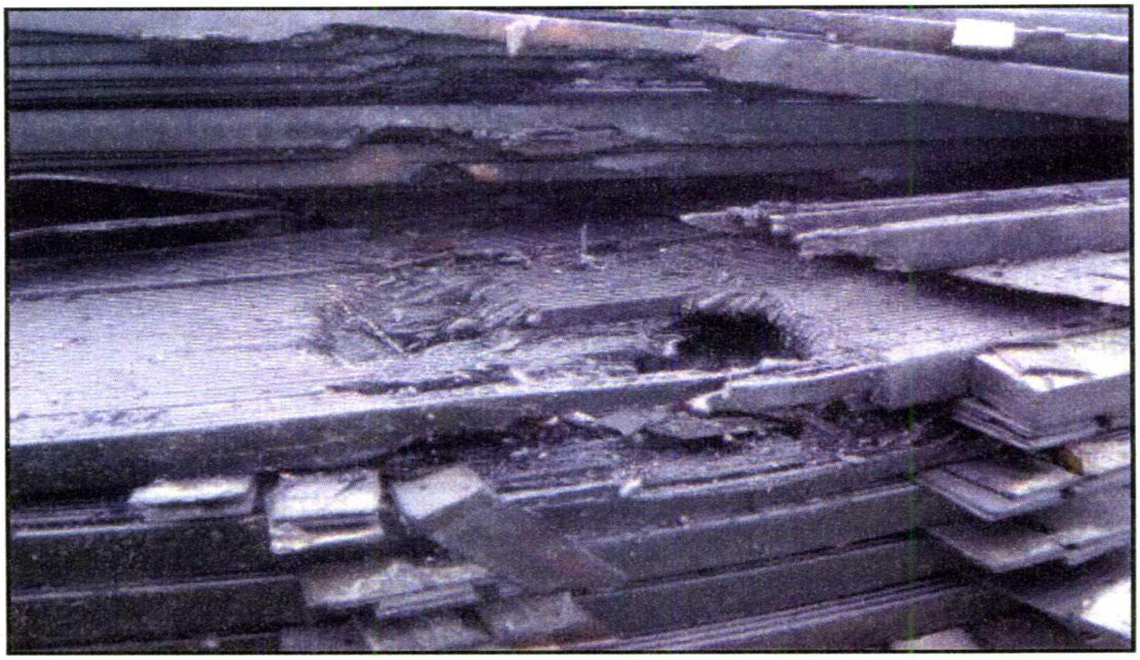


Figure 1.5 – Failure of transformer by shorted turns (reproduce from reference [6] with permission)

The previous methods which have been proposed towards improving the differential relay and detecting internal turn-to-turn faults within the power transformer are outlined in the paragraphs below.

Sachdev, Sidhu and Wood presented a digital relaying algorithm for detecting transformer winding faults [19]. This principle is based on checking whether the differential equation combined from the equations at the primary and secondary windings is valid. The electro-magnetic equations of a transformer are differential equations of currents, voltages and mutual flux linkages. The differential equations are valid during normal operating conditions, magnetizing inrush and external faults. However, they are not valid during internal faults. If the power transformer is connected in Y-Y, the fault can be detected directly because the winding current is available. However, if the power transformer is connected in Y-Δ, then each of the three equations contains the unavailable Δ winding current causing this algorithm to decompose the winding currents into non-circulating and circulating currents. According to the results presented in this paper, the proposed technique was effective for 5% of shorted turns of the winding.

Kang, Lee and et al described a transformer protection based on the increment of the flux linkages [20]. The ratio of the increments of the primary and the secondary winding flux linkages is equal to the turn ratio during normal operating conditions, magnetizing inrush current and over-excitation. During internal winding faults, it will differ from the turn's ratio. However, the ratio of the increments of the flux linkages is not always equal to the turn ratio because the increments of the flux linkages of the primary and secondary windings are instantaneous values and consequently pass through zero. According to the presented result, the proposed technique is effectively limited to a turn-to-turn fault involving more than 10% of the winding.

Jiang, Bo and et al proposed power transformer protection based on transient detection using Discrete Wavelet Transform (DWT) [21]. The protection technique in this paper focuses on the features of fault transient currents instead of the fault under fundamental frequency. To detect the transformer fault, only the dominant transient within the certain bands plays the important role. The average and differential currents between the primary and the secondary currents are derived from the DWT outputs. To obtain the restraining and operating current, the spectral energies of the average and differential currents are calculated using the moving average process. To determine whether the fault is internal or external to the transformer, the relay compares the levels of the operating and restraining current.

Ngaopitakkul and Kunakorn presented an algorithm based on a combination of Discrete Wavelet Transform and neural networks for detecting and classification of internal faults in two winding three phase transformer [22]. According to this method, the current waveforms are extracted to several scales with the Wavelet transform, and the coefficients of the first scale from the Wavelet transformer are investigated. The comparison of the coefficients was performed and used as inputs for the training process of the neural networks.

Khorashadi-Zadeh and Li presented a sensitive artificial neural network (ANN) based differential relay for fault identification in power transformer protection [23]. In this proposed algorithm, different transient states are considered as different patterns. These different patterns are recognized by an artificial neural network. Inputs to an artificial neural network are the harmonics of the positive sequence of differential current. In this method the inputs are the $1^{st}$, $2^{nd}$, and $5^{th}$ harmonic components of the positive sequence differential current. The drawback of using methods based on neural networks is that these methods require a large number of training patterns which are produced by simulation of various cases and this method is not generalized to be applied to different power transformers.

In 2005, Gajic, Brncic, Hillstrom and et al from ABB (Sweden) in a conference paper discussed about a new differential protection method based on negative sequence currents for detecting turn-to-turn faults within the power transformer [24]. According to the new method, the relay will look into the phase angle shift between negative sequence current components from different sides of the transformer and will make decisions based on this phase angle shift. According to reference [24], the new sensitive method can be used for detecting minor internal turn-to-turn faults in the power transformer. Studies presented in this paper were very limited – it dealt with one particular configuration and one system condition. The results given in this paper were also not convincing because of limited studies performed for only one set of system parameters and no detailed investigations.

Past researchers faced problems while using negative sequence currents for detecting minor turn-to-turn faults within the power transformer. According to reference [25], the changes in impedance of the total phase circuit for a shorted turn is very difficult to calculate because of the power transformer actions. In accordance with their estimations when the impedance in the faulted phase changes by 3%, the negative and zero sequence currents will not be sufficiently large enough and will be less than 1%. Their rational is as follows: the magnitudes of the currents largely depend on the total reactor impedance as the source impedance is relatively low compared to the reactor impedance. Also, it is worth noting that removing the ground from the unit will not affect the magnitudes of the positive and negative sequence currents significantly, but it will eliminate the zero sequence currents because there will not be a path for the zero sequence currents to flow through.

The literature review discussed in previous paragraphs showed that detecting minor internal turn-to-turn faults within the power transformer is a very difficult problem. Some special schemes or relays have to be designed and can be used as customized application.

The thesis focus work is on developing a negative sequence protection scheme for detecting internal turn-to-turn faults within the power transformer for various operating conditions and different configurations of the power transformer. The main motivation of this research was to verify if this proposed method is able to perform better than the traditional differential protection method.

## 1.4 Objectives of the research

As described above, the primary objective of this thesis is to investigate the possibility of using the protection technique, which is based on negative sequence currents, for detecting minor turn-to-turn faults in transformers in order to improve the performance of the traditional transformer differential protection. The second objective is to verify how accurately internal turn-to-turn faults can be detected within the power transformer using this new protection technique. The final objective is to investigate the performance of the new protection method based on negative sequence currents under different numbers of shorted turns of the transformer, different connections of the power transformer, different values of the fault resistances, different values of the system parameters, and during the CT saturation.

## 1.5 Outline of the thesis

This thesis is organized in six Chapters and two Appendices. A brief introduction to the power transformers and a brief overview about existing transformer protection schemes, which are currently used for protection of power transformers, is described in the first chapter. The problem with detecting minor internal faults within the power transformer is stated. Objectives of the research are drawn from the literature review on transformer protection against internal turn-to-turn faults. The organization of the thesis is discussed as well.

In Chapter 2, a detailed description about symmetrical components and sequence networks for various types of common faults and an internal turn-to-turn fault in power transformers is presented.

The new protection method is presented in Chapter 3. Also, logic of the proposed technique based on negative sequence currents is introduced in this chapter.

Chapter 4 discusses simulation of the power system. Furthermore, the detailed description of the model of the proposed technique based on negative sequence currents and the traditional differential protection model are presented in this chapter.

Chapter 5 shows the studies of the performance of the traditional differential protection and the proposed technique based on negative sequence currents. The performance of the proposed technique under different connections of the power transformer, different numbers of shorted turns of the power transformer, different values of the fault resistances, different values of the system parameters, during the CT saturation, and the inrush current is investigated, as well as the performance of the traditional differential protection.

Chapter 6 summarizes the research work described in the thesis and presents general conclusions.

Data and parameters of the modelled power system are presented in Appendix A.

Performance of the proposed method for the power transformer connected in Δ/Y is given in Appendix B.

# CAHPTER 2
# UNSYMMETRICAL FAULTS

## 2.1 Symmetrical components

This research introduces the protection technique, which can improve differential relay sensitivity for minor internal turn-to-turn faults. This technique is based on the theory of symmetrical components, more exact, on negative sequence currents. According to Fortescue's theorem, three unbalanced phasors of a three phase system can be resolved into three balanced systems of phasors [26] - [29]. The unbalanced set of current phasors is depicted in Figure 2.1

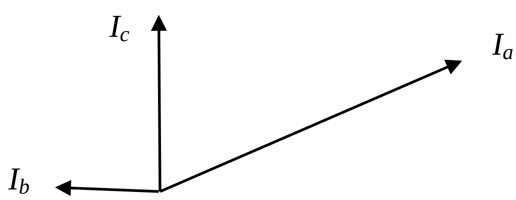



Figure 2.1 – Unbalanced current phasors

The balanced sets of components are (Figures 2.2 - 2.4):

1. *Positive sequence components*

   This sequence consists of three phasors which are equal in magnitude, displaced from each other by 120 degrees in phase, and have the same phase sequence as the original $I_{abc}$.

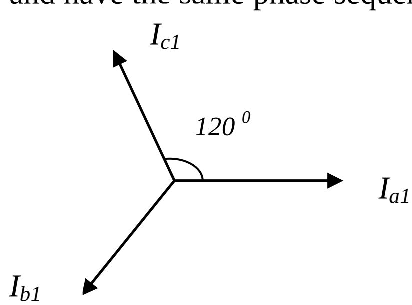



Figure 2.2 – Positive sequence components

*2. Negative sequence components*

This sequence consists of three phasors which are equal in magnitude, displaced from each other by 120 degrees in phase, and have the phase sequence $I_{acb}$ which is opposite to the original phasors.

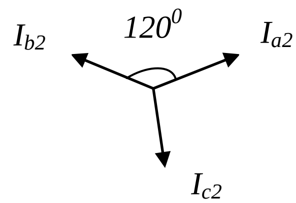



Figure 2.3 – Negative sequence components

*3. Zero sequence components*

This sequence consists of three phasors which are equal in magnitude and with zero phase displacement from each other.

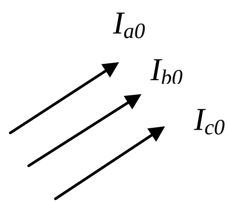



Figure 2.4 – Zero sequence components

This method converts three unbalanced phases into three independent sources.

For example, a vector for three phase currents can be written as:

$$I_{abc} = \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{2.1}$$

Where $I_a$ - the current in phase A,

$I_b$ - the current in phase B,

$I_c$ - the current in phase C.

The three symmetrical components can be written as:

$$I_{012} = \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} \tag{2.2}$$

Where $I_0$ - the zero sequence component,

$I_1$ - the positive sequence component,

$I_2$ - the negative sequence component.

Phases are rotated forward by 120 degrees. A phase rotation operator *a* is defined to rotate a phasor vector. Using the *a* operator, the double subscript notation which was used in Figures 2.2 - 2.4 can be eliminated. This can be done by expressing each phasor in terms of phase A phasor.

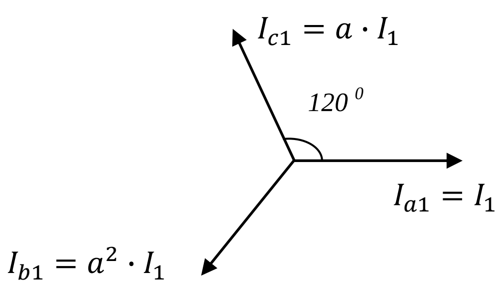



Figure 2.5 – Positive sequence components expressed in terms of phase A quantities

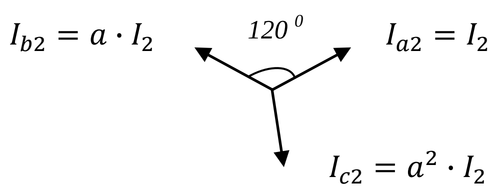



Figure 2.6 – Negative sequence components expressed in terms of phase A quantities

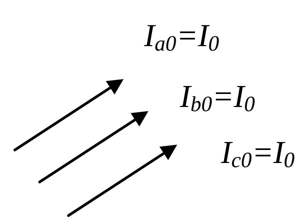



Figure 2.7 – Zero sequence components expressed in terms of phase A quantities

The symmetrical components have to satisfy the constraint which states that the vector sum of symmetrical components equals the original set of unbalanced phasors [26]. The sum of the sequence components is depicted in Figure 2.8.

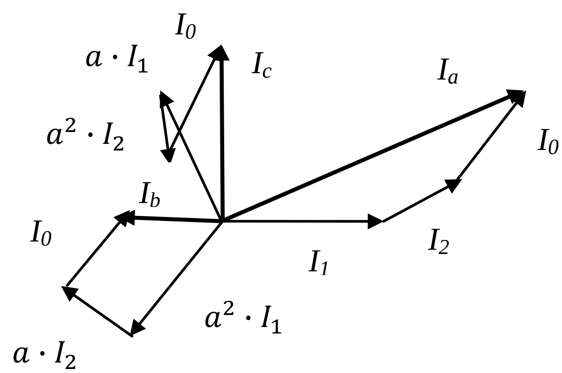



Figure 2.8 – Sum of sequence components

The unbalanced currents can be expressed as the sum of their components:

$$I_a = I_0 + I_1 + I_2 \tag{2.3}$$

$$I_b = I_0 + a^2 I_1 + a I_2 \tag{2.4}$$

$$I_c = I_0 + a I_1 + a^2 I_2 \tag{2.5}$$

A matrix $A$ can be defined using this operator to transform the phase vector (*ABC*) into symmetrical components (*012*).

$$A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \tag{2.6}$$

The phase currents generated by the sequence components can be written as:

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \cdot \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} \tag{2.7}$$

Conversely, the sequence components which are generated from the phase currents can be written as:

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = A^{-1} \cdot \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{2.8}$$

Where $A^{-1}$ - the inverse matrix.

$$A^{-1} = \frac{1}{3} \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \tag{2.9}$$

Then equation (2.8) can be written as:

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \cdot \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{2.10}$$

Then equation 2.10 can be written as:

$$I_0 = \frac{1}{3}(I_a + I_b + I_c) \tag{2.11}$$

$$I_1 = \frac{1}{3}(I_a + aI_b + a^2 I_c) \tag{2.12}$$

$$I_2 = \frac{1}{3}(I_a + a^2 I_b + aI_c) \tag{2.13}$$

In a three phase system, the sum of the line currents ($I_a$, $I_b$, $I_c$) is equal to the current $I_N$ in the return path through the neutral [27] - [29]:

$$I_a + I_b + I_c = I_N \tag{2.14}$$

As it can be seen from Equation 2.11:

$$I_N = 3I_0 \tag{2.15}$$

If there is no path through the neutral of a three phase system, then the current $I_N$ is zero and the line currents contain no zero components.

## 2.2 Sequence impedances for the power transformer

When positive sequence currents are present, the impedance is called the positive sequence impedance. When negative sequence currents are present, the impedance is called the negative sequence impedance. And when only zero sequence currents are present, then the impedance is called the zero sequence impedance [26] - [29].

For all power transformers, the positive, negative, and zero sequence impedances are the same.

$$Z_1 = Z_2 = Z_0 = Z_l \tag{2.16}$$

Where $Z_1$ - the positive sequence impedance,

$Z_2$ - the negative sequence impedance,

$Z_0$ - the zero sequence impedance,

$Z_l$ - the leakage impedance.

The sequence impedance of the power transformer is the total leakage impedance of the transformer.

The primary and the secondary windings of the power transformer can be connected in either delta (Δ) or wye (Y) configurations. There are four possible combinations of connection: Δ-Δ, Δ-Y, Y-Δ, Y-Y.

When a system has a transformer with Δ-Y connection, the effect of the Δ-Y transformer phase shift on fault currents has to be considered. The positive quantities on the high voltage side of the transformer will be 30 degrees greater than the positive quantities on the low voltage side of the transformer [27] - [29]. The negative sequence quantities are the reverse of the positive sequence quantities. In other words, the negative sequence quantities on the high voltage side of the transformer will lead the negative sequence quantities on the low voltage side of the transformer by -30 degrees.

The equivalent circuit for the zero sequence impedance depends on the power transformer winding connections.  As it is known, zero sequence currents will flow only if there is a return path through which a completed circuit is provided [26] - [29].

All possible combinations of the transformer winding connections are discussed in the following paragraphs.

If the power transformer is connected in Y-Y and both neutrals are grounded, then there is a path for zero sequence current to flow in both windings of the transformer.  The equivalent zero sequence circuit for this connection is depicted in Figure 2.9.

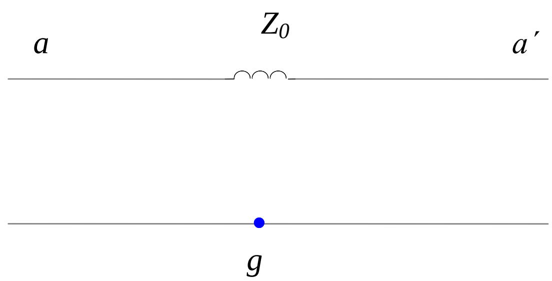



Figure 2.9 – The equivalent zero sequence circuit for Y-Y connections with both neutrals grounded

If the power transformer is connected in Y-Y with the primary neutral grounded and the secondary neutral isolated, then the zero sequence current in the secondary winding is zero. Consequently, the zero sequence current in the primary winding will be zero.  The equivalent zero sequence circuit for this connection is depicted in Figure 2.10.

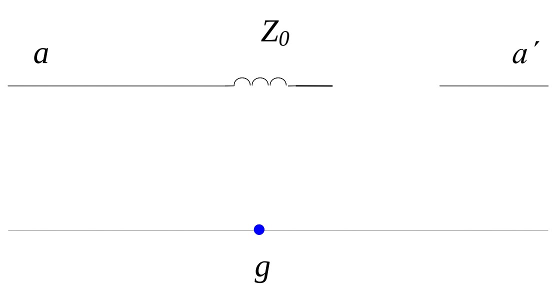



Figure 2.10 – The equivalent zero sequence circuit for Y-Y connections with the primary neutral grounded and the secondary neutral isolated

If the power transformer is connected in Δ-Δ, then the zero sequence current will circulate in the Δ connected windings, but no current can leave the Δ terminals. The equivalent zero sequence circuit for this connection is depicted in Figure 2.11.

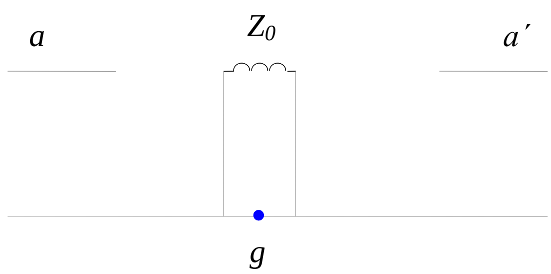



Figure 2.11 – The equivalent zero sequence circuit for Δ-Δconnections

If the power transformer is connected in Y-Δ and neutral is grounded, then the primary currents can flow because there is zero sequence circulating current in the secondary winding connected in Δ and a ground return path for the primary winding connected in Y.  For these connections, there is isolation between the primary and the secondary windings because zero sequence current cannot leave the Δ terminals.  The equivalent zero sequence circuit for this connection is depicted in Figure 2.12.

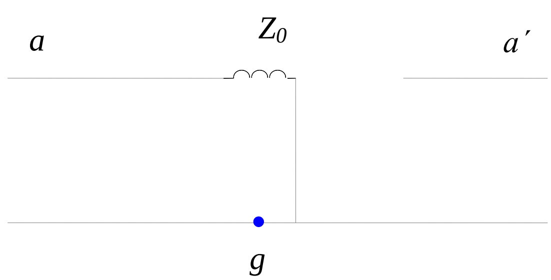



Figure 2.12 – The equivalent zero sequence circuit for Y-Δ connections with neutral grounded

If the power transformer is connected in Y-Δ and neutral is isolated, then the zero sequence current cannot flow and the equivalent circuit reflects infinite impedance.  The equivalent zero sequence circuit for this connection is depicted in Figure 2.13.

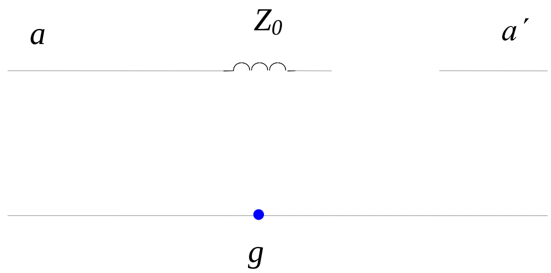



Figure 2.13 – The equivalent zero sequence circuit for Y-Δ connections with neutral isolated

## 2.3 Sequence network connections and symmetrical components for various types of common faults

Before the fault occurs, the system operates under steady-state conditions. The pre-fault system is balanced and the zero, positive, and negative sequence networks are uncoupled [27] - [29].

The sequence components $I_0$, $I_2$ are equal to zero before the fault occurs. During unsymmetrical faults, sequence networks carrying the currents $I_0$, $I_1$ and $I_2$ are interconnected at the fault location to present various unbalanced fault conditions. The presence of the negative and zero sequence components is an indication of abnormal conditions (faults).

Since the new method is based on negative sequence currents, the negative sequence current for different types of fault has to be observed.

Unbalanced faults such as phase-to-phase, phase-to-ground, and phase-to-phase-to-ground produce negative sequence current. From the negative sequence current standpoint, phase-to-phase fault is the most severe fault. The reason for this can be seen from the sequence network diagrams.

The sequence network diagrams for three different fault conditions (phase-to-phase, phase-to-ground, phase-to-phase-to-ground faults) are depicted in Figures 2.14 - 2.16.

**1. Phase-to-ground fault**

The negative sequence current resulting from phase-to-ground fault is limited by the positive ($Z_1$), negative ($Z_2$), zero ($Z_0$) sequence impedances and the fault impedance ($Z_f$). In case of the bolted fault, the fault impedance equals zero.

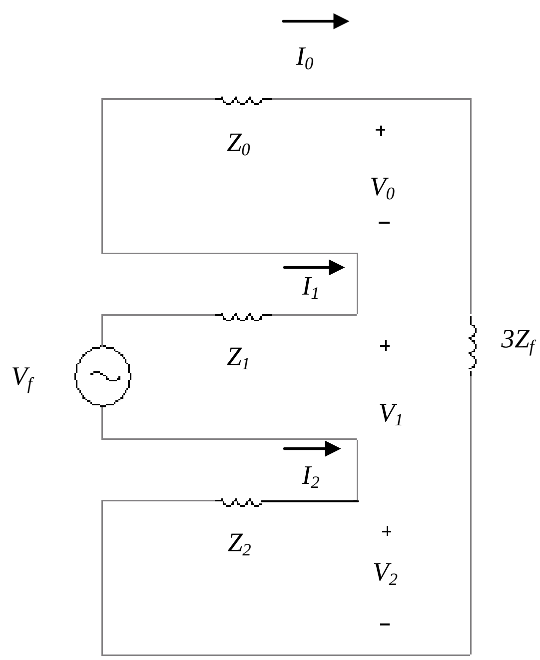



Figure 2.14 – The sequence connection for phase-to-ground fault

The sequence components of the fault currents are:

$$I_2 = I_1 = I_0 = \frac{V_f}{Z_0 + Z_1 + Z_2 + 3Z_f} \quad (2.17)$$

Where $V_f$ - the pre fault voltage.

The sequence fault currents can be transformed to the phase domain using equation 2.7.

**2. Phase-to-phase fault**

The negative sequence current which results from the phase-to-phase fault is limited only by the positive ($Z_1$), negative ($Z_2$) sequence impedances, and the fault impedance ($Z_f$).

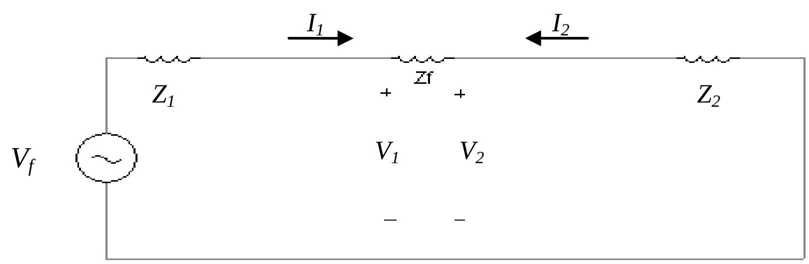



Figure 2.15 – The sequence connection for phase-to-phase fault

The sequence faults current are:

$$I_2 = -I_1 = \frac{V_f}{Z_1+Z_2+Z_f} \tag{2.18}$$

The negative sequence current resulting from the phase-to-phase fault will be higher than the negative sequence current resulting from phase-to-ground fault.

### 3. Phase-to-phase-to-ground fault

For the phase-to-phase-to-ground fault, the sequence connection shows that the positive, negative and zero sequences are connected in parallel at the fault terminal. This connection will result in higher positive sequence current. However because the current split between the negative and zero network sequences, the resulting negative sequence current is usually less than that for the phase-to-phase fault.

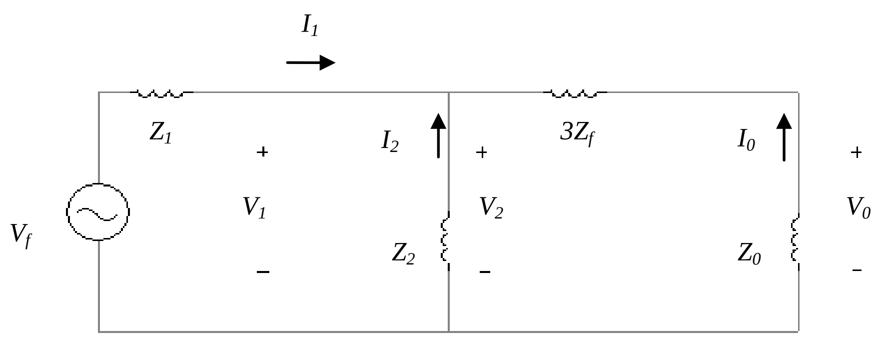



Figure 2.16 – The sequence connection for phase-to-phase-to-ground fault

The positive sequence fault current is:

$$I_1 = \frac{V_f}{Z_1 + \frac{Z_2(Z_0+3Z_f)}{Z_2+Z_0+3Z_f}} \tag{2.19}$$

Using current division in Figure 2.16, the negative sequence fault current is:

$$I_2 = (-I_1)\frac{Z_0+3Z_f}{Z_0+3Z_f+Z_2} \tag{2.20}$$

The zero sequence fault current is:

$$I_o = (-I_1)\frac{Z_2}{Z_0+3Z_f+Z_2} \tag{2.21}$$

## 2.4 Sequence network connections and symmetrical components for turn-to-turn faults in power transformers

A turn to-turn fault is a short circuit of a few turns in the power transformer winding. When a few turns are shorted in one phase, then the impedance of the shorted phase is not equal to the impedances of the other two phases [25], [29]. According to reference [25], the impedance change in one phase can be represented as a shunt unbalance as shown in Figure 2.17 for a grounded transformer. Figure 2.18 depicts the corresponding sequence network for a turn-to-turn fault.

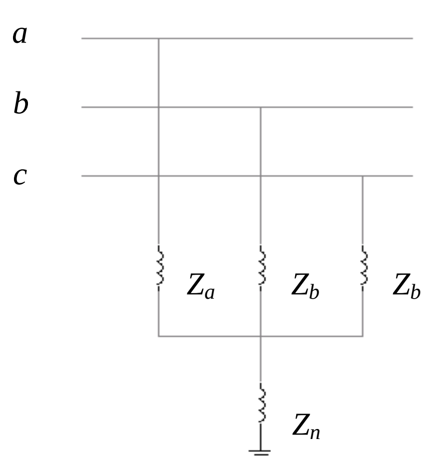



Figure 2.17 – Shunt unbalance with a shorted turn in phase A

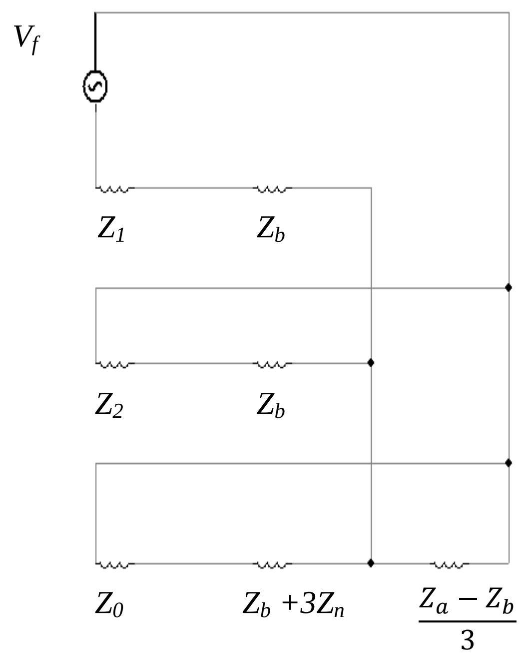



Figure 2.18 – Sequence network for a turn-to-turn fault in phase A

As it was mentioned before in Chapter 1, the traditional differential relay is not sensitive enough to detect minor internal turn-to-turn faults in the power transformer because the changes in the phase current are quite small.

The new protection technique for turn-to-turn fault is based on the negative sequence currents. Negative sequence currents superimpose pure-fault quantities. Negative sequence currents have the advantage over the zero sequence currents. It is known that removing the ground from the unit will eliminate zero sequence components. However, negative sequence currents are produced even when the fault does not include earth.

Figures 2.19 - 2.21 show phase currents ($I_{SC1}$ and $I_{SC2}$) and negative sequence currents ($I_{NS\_P}$ and $I_{NS\_S}$) on both sides of the transformer during the steady-state condition and during the fault when 5%, 3% and 1% of turns are shorted on the secondary side of the power transformer in phase C.

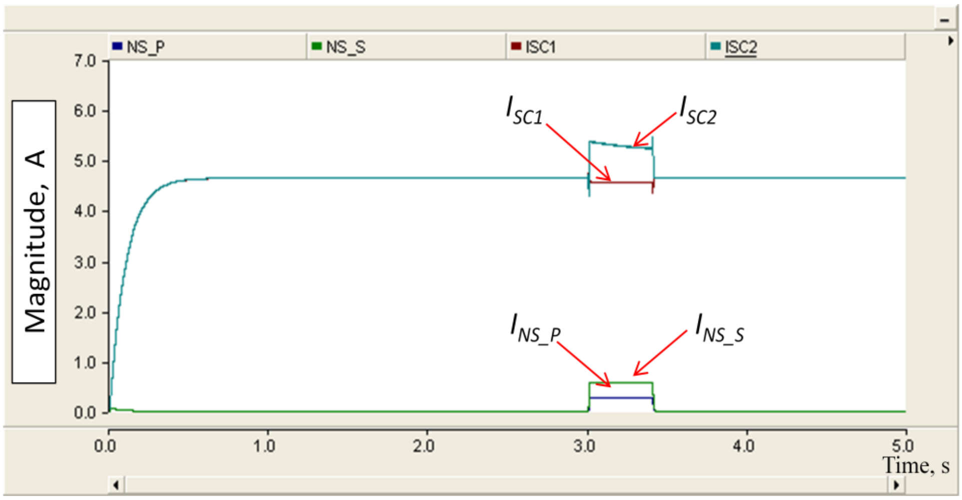



Figure 2.19 – Phase currents and negative sequence currents during the steady-state condition and during the fault for 5% shorted turns

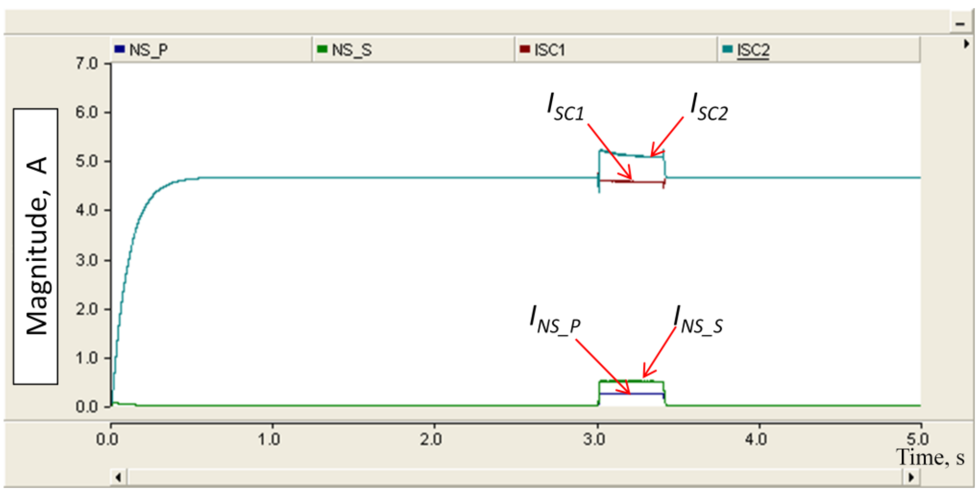



Figure 2.20 – Phase currents and negative sequence currents during the steady-state condition and during the fault for 3% shorted turns

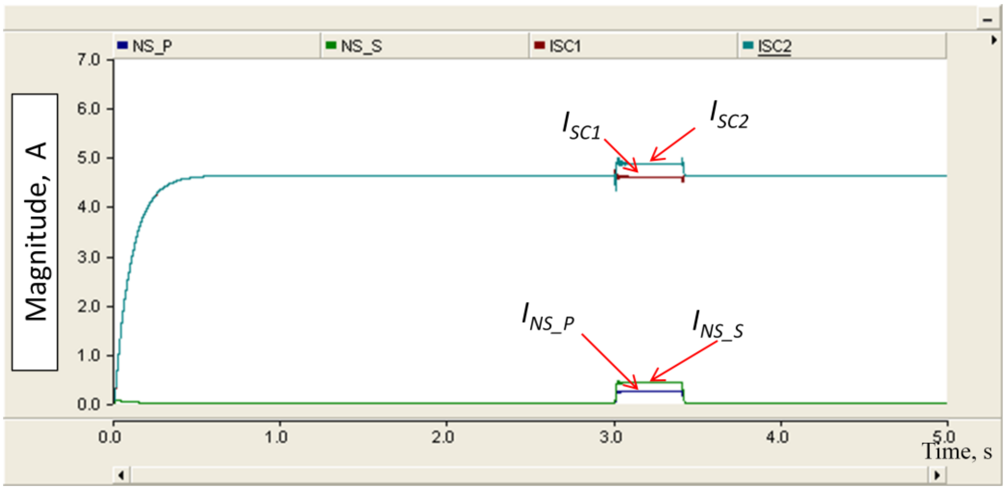



Figure 2.21 – Phase currents and negative sequence currents during the steady-state condition and during the fault for 1% shorted turns

In the figures:

$I_{SC1}$ - secondary phase current produced by CT on the primary side of TR in phase C,

$I_{SC2}$ - secondary phase current produced by CT on the secondary side of TR in phase C,

$I_{NS\_P}$ - negative sequence current on the primary side of TR scaled down using CT,

$I_{NS\_S}$ - negative sequence current on the secondary side of TR scaled down using CT.

As it can be seen from Figures 2.19 - 2.21, the changes in magnitudes of the negative sequence currents on both sides of the power transformer during the fault compared to the steady state value of the phase currents are greater than the change in magnitude of the phase currents for a turn-to-turn fault.

The changes in magnitudes of the phase currents and negative sequence currents during the steady state condition and during an internal turn-to-turn fault when 5%, 3% and 1% of turns are shorted on the secondary side of the power transformer are shown in Table 2.1 - 2.3.

Table 2.1 – Magnitudes of the phase currents and negative sequence currents during steady-state condition and during an internal turn-to-turn fault for 5% shorted turns

| *Sequence components* | *Steady-state, A* | *Fault, A* | *Change, %* |
|---|---|---|---|
| $I_{SC1}$ | 4.62 | 4.54 | 1.76 |
| $I_{SC2}$ | 4.62 | 5.29 | 12.6 |
| $I_{NS\_P}$ | 0.0014 | 0.26 | 99.46 |
| $I_{NS\_S}$ | 0.0014 | 0.57 | 99.75 |

Table 2.2 – Magnitudes of the phase currents and negative sequence currents during steady-state condition and during an internal turn-to-turn fault for 3% shorted turns

| *Sequence components* | *Steady-state, A* | *Fault, A* | *Change, %* |
|---|---|---|---|
| $I_{SC1}$ | 4.63 | 4.55 | 1.75 |
| $I_{SC2}$ | 4.63 | 5.11 | 9.39 |
| $I_{NS\_P}$ | 0.0014 | 0.24 | 99.41 |
| $I_{NS\_S}$ | 0.0014 | 0.50 | 99.72 |

Table 2.3 – Magnitudes of the phase currents and negative sequence currents during steady-state condition and during an internal turn-to-turn fault for 1% shorted turns

| *Sequence components* | *Steady-state, A* | *Fault, A* | *Change, %* |
|---|---|---|---|
| $I_{SC1}$ | 4.62 | 4.60 | 0.43 |
| $I_{SC21}$ | 4.62 | 4.85 | 4.75 |
| $I_{NS\_P}$ | 0.0014 | 0.23 | 99.39 |
| $I_{NS\_S}$ | 0.0014 | 0.42 | 99.66 |

## 2.5 Summary

This chapter introduces the concept of the symmetrical components technique. The symmetrical components technique is very important in the analysis and design of a three-phase power system. The symmetrical components method is a very important tool for unsymmetrical short-circuit studies. A linear transformation from phase components (*ABC*) to symmetrical components (*012*) is shown. The sequence networks and symmetrical components for different types of common faults and an internal turn-to-turn fault in the power transformer are presented.

# CHAPTER 3

# SENSETIVE TURN-TO-TURN FAULT DETECTION USING NEGATIVE SEQUENCE CURRENTS

## 3.1 Introduction to the new transformer protection method

The existence of negative sequence currents beyond the normal or tolerable unbalances is proof of a fault in the power transformer windings. Negative sequence currents do not exist during the symmetrical three phase fault. They do exist during unsymmetrical faults long enough for the relay to make the proper decision. Negative sequence currents have an advantage compared to zero sequence currents because they can provide coverage for phase-to-phase and turn-to-turn faults as well as for ground faults.

The algorithm for the new turn-to-turn fault detection is based on negative sequence currents and derived from the theory of symmetrical components explained in Chapter 2 [29].

It is known from the theory of symmetrical components that:

1. Negative sequence currents can distribute through the negative sequence network.
2. The source of negative sequence currents at the point of the fault is: $E_{NS} = -I_{NS} \cdot Z_{NS}$
3. Negative sequence currents obey Kirchhoff's first law which states that at any point in an electrical circuit, the sum of currents flowing towards that point is equal to the sum of currents flowing away from that point.

The following sections describe flow of negative sequence currents for the power transformer external and internal faults.

### 3.1.1 Flow of the negative sequence currents for transformer external faults

If the fault is external to the power transformer, then the source of the negative sequence fault currents will be outside of the protected zone as shown in Figure 3.1. For the external faults in the transformer, negative sequence current (*INS_P*) will enter the healthy transformer on the faulty side and negative sequence current (*INS_P′*) will leave on the other side as shown in Figure 3.1. Then, negative sequence currents on the respective sides of the power transformer will have opposite direction. This means that the phase shift between these two phasors will be equal to 180 º.

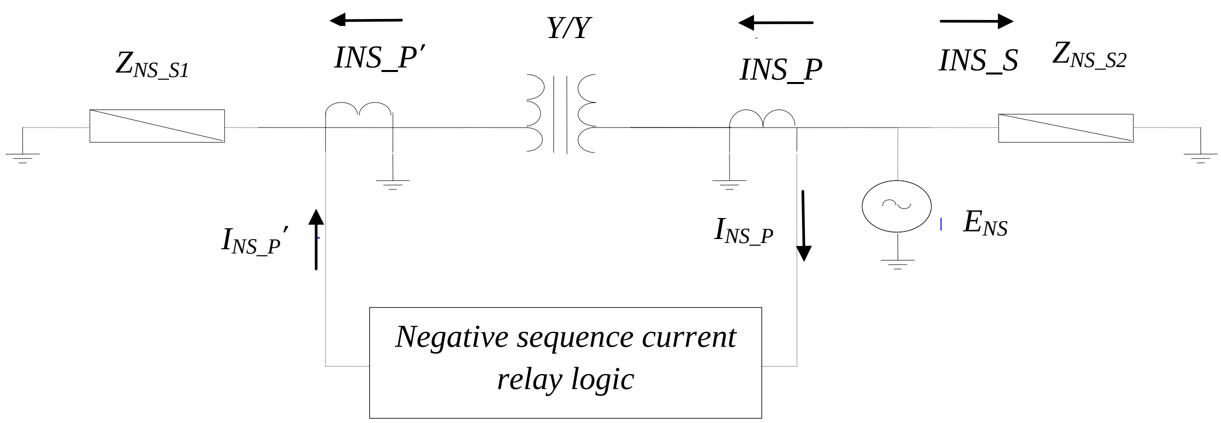



Figure 3.1 – Flow of negative sequence currents for transformer external fault

In Figures 3.1and 3.2:

$Z_{NS\_S1}$, $Z_{NS\_S2}$ - the negative sequence impedances for the equivalent sources $S_1$ and $S_2$,

$E_{NS}$ - fictitious negative sequence source,

*INS_P*, *INS_S* - the negative sequence currents on the primary and secondary side of TR,

*INS_P′*- the negative sequence current transformed from the fault side to the other side of TR,

$I_{NS\_P}$, $I_{NS\_S}$ - the negative sequence currents on the primary and secondary side of TR scaled down using CTs.

### 3.1.2 Flow of the negative sequence currents for transformer internal faults

If the fault is internal to the power transformer, then the source of the negative sequence fault currents will be inside of the protected zone as shown in Figure 3.2. For the internal faults in the transformer, negative sequence currents (*INS_P* and *INS_S*) will flow out of the faulty transformer on both sides as shown in Figure 3.2. Then negative sequence currents on the respective sides of the power transformer will have the same direction. This means that the phase shift between these two phasors will be equal to 0 º.

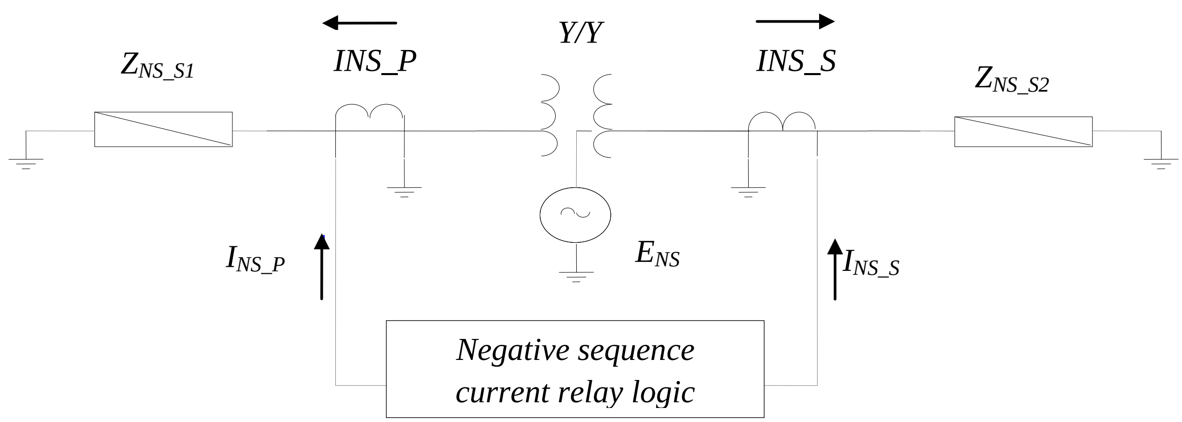



Figure 3.2 – Flow of negative sequence currents for transformer internal fault

## 3.2 The description of the new negative sequence current based protection method

For this method to be successful, the negative sequence components on the two sides of the protected power transformer have to be significant. The new protection technique operates depending on the relative position of two phasors. In other words, this protection scheme will compare the phase angle shift between the negative sequence current on the primary side of the transformer and the negative sequence current on the secondary side.

However, the comparison between the negative sequence currents on the primary and secondary sides of the power transformer is valid for non-zero phase displacement transformers and turns ratio equal to 1. In other words, this comparison is valid for the Δ-Δ or Y-Y connection of the transformer windings, and for the turn ratio equal to 1. If the phase displacement of the transformer differs from zero degrees and the turn ratio differs from 1, then the phase shift and turns ratio of the transformer have to be compensated in order to use this method. The Δ-Y connection of three phase power transformers introduces a 30 degree phase shift between the primary and the secondary windings. A 30 degree phase shift between the primary and the secondary winding of the power transformer can be compensated by the correct selection of interposing current transformers windings connections. The correct selection of interposing current transformers ratio allows compensating for current magnitude differences on different sides of the power transformer.

The logic of the protection method based on negative sequence currents for detecting an internal turn-to-turn fault within the power transformer is shown in Figure 3.3.

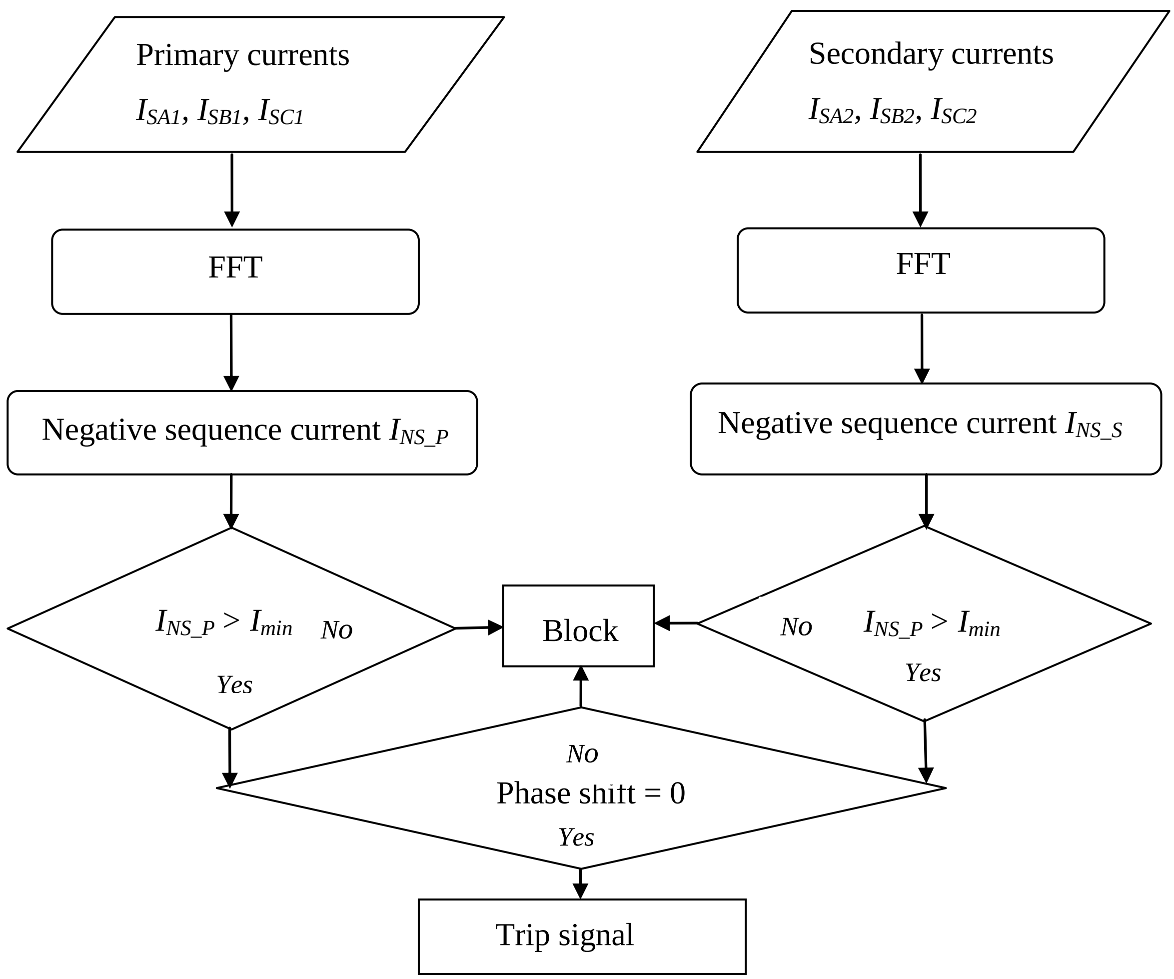



Figure 3.3 – Negative sequence current based logic

As it can be seen from the Figure 3.3, the logic of the protection method based on negative sequence currents has two steps:

1. Firstly it checks for the magnitude of negative sequence current components on both sides of the power transformer.
2. The second step is to check for the phase angle shift between these two phasors.

***The logical steps are explained in detail below:***

1. All individual instantaneous currents on the primary side ($I_{SA1}$, $I_{SB1}$, $I_{SC1}$) and on the secondary side ($I_{SA2}$, $I_{SB2}$, $I_{SC2}$) of the power transformer have to be measured.

2. Using the Fast Fourier Transform (FFT) block determines the fundamental harmonic magnitude and phase of the input signal as a function of time.

3. Calculate negative sequence currents on the primary side ($I_{NS\_P}$) and on the secondary side ($I_{NS\_S}$) of the power transformer (i.e. magnitude and phase components of the fundamental harmonic).

4. Check the magnitudes of negative sequence currents from both sides of the transformer and compares them with a pre-set level. The magnitudes of negative sequence currents from both sides of the power transformer have to be above the pre-set limit in order to check the relative position (phase angle) between these two phasors. The minimum pre-set level has to be above values which can be measured during normal operation of the power system. The limit value has to be set in the range within 1% to 20% of the differential protection's base current. The differential protection's base current is the power transformer's high voltage side rated current. The reason for this condition is to exclude the negative sequence currents which can be introduced due to the pre-fault asymmetries of the power system (tolerable imbalances).

If the contribution of negative sequence currents from both sides of the power transformer is less than a pre-set level, then a directional comparison is not done to avoid the possibility of making a wrong decision and the relaying logic will block.

But if the contribution of negative sequence currents from both sides of the transformer is more than a pre-set level, then a directional comparison can be done and a phase angle between two phasors of negative sequence currents can be found.

5. If the phase shift between two phasors of negative sequence currents is $0^{o}$, then an internal fault is indicated and a trip command issued.

## 3.3 Summary

This chapter gives an overview on the new transformer differential protection method. The logic of negative sequence currents based protection method is described. In order to apply this method for detecting internal faults within the power transformer, the phase shift and turns ratio have to be compensated. According to the new method, the differential relay will look into the phase angle shift between negative sequence current components from different sides of the power transformer and will make decisions depending on the relative position of two phasors.

# CHAPTER 4
# PSCAD/EMTDC MODELING OPF THE POWER TRANSFORMER AND THE DIFFETENTIAL RELAY

## 4.1Tools required to model the power system and differential relays

The PSCAD/EMTDC ™ software (version 4.2.1) has been used to model the power system and to design the traditional differential relay model and the differential relay based on negative sequence currents models. PSCAD/EMTDC is the simulation tool for analyzing power system transient developed by Manitoba HVDC Research Centre [31]. The PSCAD/EMTDC software gives a complete library with the typical elements required to model the typical power system.

## 4.2The modeled power system

The system under study is a two machine power system connected through a three phase power transformer. A three phase transformer bank was constructed using three single phase transformers, each of 33.3 MVA, 23/132 kV. The simulated power system model is depicted in Figure 4.1. To validate the model, the steady state operation and the transient behaviour during faults were compared with theoretical calculations.

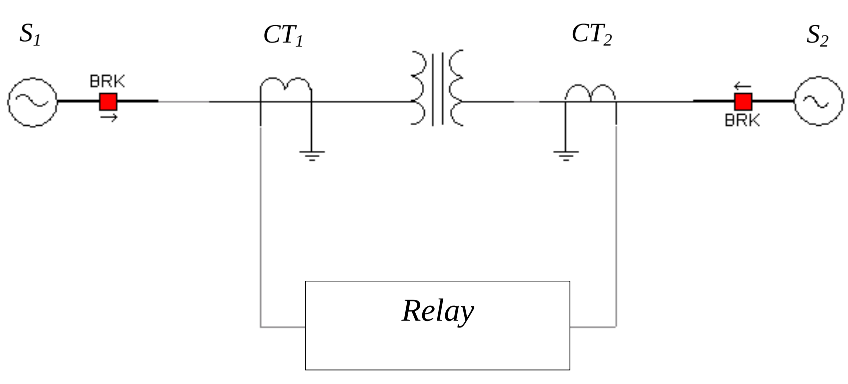



Figure 4.1 – Simulated power system model

The simulated power system model includes:

- Voltage sources ($S_1$ and $S_2$).
- Circuit breakers (*BRK*).
- Current transformers ($CT_1$ and $CT_2$).
- A power transformer model that can simulate internal turn-to-turn faults.

### 4.2.1 Voltage sources

Two sources ($S_1$ and $S_2$) have been used in simulation. The voltage source component model which has been used to model a three phase voltage source is depicted in Figure 4.2.

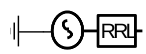



Figure 4.2 – The voltage source component model

The source impedance type can be chosen as resistive, inductive or capacitive. The parameters can be specified behind the source impedance or at the terminal. This component has an option of external control of voltage and frequency. Monitoring the source can be controlled through internal parameters or fixed parameters or variable external signals. The external inputs are:

- $V$ - line-to-ground, peak voltage magnitude, kV,
- $f$ - frequency, Hz.

The parameters of two sources are given in Tables A.1 - A.2 in Appendix A.

### 4.2.2 Circuit breakers

The circuit breaker component model is depicted in Figure 4.3. This component simulates the operation of the three phase circuit breaker. This component has an option to specify the ON (closed) and OFF (open) resistance of the breaker. The circuit breaker is controlled by the input signal (default is *BRK*).

The logic of the circuit breaker is:

- *OFF*( Open) - 1
- *ON* (Closed) - 0.

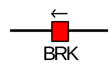



Figure 4.3 – The circuit breaker component model

### 4.2.3 Current transformers

As it can be seen from Figure 4.1, differential relay is connected to the CTs secondary windings. Current transformers (CTs) are used in the field to reduce the value of primary currents for convenience of measurement to a maximum value of 5A and provide electrical isolation from the power system. This allows personnel to work in a safer environment.

To select current transformers (CTs), rated (full-load) currents at both voltage levels have to be calculated using the formula:

$$I = \frac{S}{\sqrt{3}V} \tag{4.1}$$

Where $S$ - the maximum load,

$V$ - the rated voltage.

The CT's ratios are chosen based on the values of the full-load currents. The parameters of current transformers are given in Tables A.3 - A.4 in Appendix A. The current transformer component model is depicted in Figure 4.4.

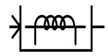


Figure 4.4 – The current transformer component model

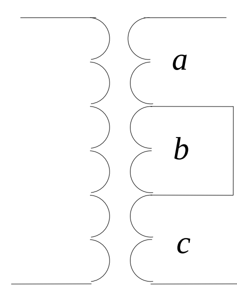
Input parameters of the current transformer are primary and secondary turns, secondary resistance and inductance, and burden resistance and burden inductance.

### 4.2.4 Power transformer model for simulating internal turn-to-turn faults

The distribution of the magnetic flux is fundamentally altered for the transformer with an internal turn-to-turn fault. To produce the magnetic flux in the core, the exciting current is required. The exciting current flows in the primary winding where it establishes an altering flux in the magnetic circuit. When an internal turn-to-turn fault occurs, the situation is more complex. To model a turn-to-turn fault, the corresponding winding is divided into three sub coils “a”, “b” and “c” as it can be seen in Figure 4.5 [32] - [34].

Figure 4.5 depicts a single phase transformer with a turn-to-turn fault. The turn-to-turn fault happened on the secondary winding, causing the secondary winding to be divided into three parts:

1) Top part - sub coil a.
2) Shorted part - sub coil b.
3) The bottom part - sub coil c.




*Primary winding* *Secondary winding*

Figure 4.5 – A single phase transformer with a turn-to-turn fault on secondary winding

Essentially, the short-circuit impedance which is mainly the leakage inductance will totally change for a mid-winding fault. A single phase transformer can be described by 4×4 matrix representing $[L]$.

$$[L] = \begin{bmatrix} L_1 & M_{1a} & M_{1b} & M_{1c} \\ M_{1a} & L_a & M_{ab} & M_{ac} \\ M_{1b} & M_{ab} & L_b & M_{bc} \\ M_{1c} & M_{ac} & M_{bc} & L_c \end{bmatrix} \tag{4.2}$$

Where $L_1$ - self-inductance in the primary winding,

$L_a$, $L_b$, $L_c$ - self-inductance of sub coils "a", "b" and "c",

$M_{1a}$ , $M_{1b}$, $M_{1c}$ - mutual inductance between primary winding and sub coils,

$M_{ab}$ , $M_{ac}$, $M_{bc}$ - mutual inductance between sub coils.

The PSCAD/EMTDC package has a standard three phase power transformer component in the library. But to detect and diagnose the internal turn-to-turn faults in transformers, a model of the transformer with an internal turn-to-turn faults is required.

PSCAD/EMTDC software allows the designing of a new component. Components in PSCAD/EMTDC are a graphic representation of the model which allows supplying input parameters and performing pre-calculation on input data. A new component can be created in PSCAD/EMTDC using the *Component Wizard*. The new component is represented by an icon in graphical interface PSCAD/EMTDC, an internal code in FORTRAN and dialog boxes. The function of the internal code is to process the inputs and retrieves outputs. The dialog boxes of the PSCAD/EMTDC component allow setting values to parameters of the internal code of the new component. The new component can interact with other components in PSCAD/EMTDC.

Figure 4.6 shows a new created component – a single phase power transformer with internal turn-to-turn faults which has been used to model the power system and to simulate turn-to-turn faults.

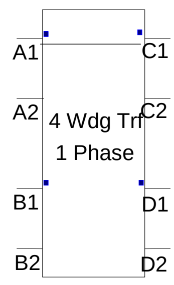



Figure 4.6 – A graphic representation of a single phase transformer with internal turn-to-turn faults

Where $A_1$-$A_2$ - primary winding of the transformer,

$B_1$-$B_2$ - top part of the secondary winding of the transformer,

$C_1$-$C_2$ - shorted part of the secondary winding of the transformer,

$D_1$-$D_2$ - the bottom part of the secondary winding of the transformer.

Input parameters of the power transformer are:

1) System frequency.
2) Transformer MVA.
3) Nominal voltage of each sub coil.
4) Leakage reactance of each sub coil.

#### 4.2.4.1 The calculation of the leakage reactance of the power transformer

The load current flows into the winding results in the magnetic field around the winding. This field is the leakage flux field which exists in the spaces occupied by the windings and in the spaces between windings. The leakage flux results in the impedance between windings. This impedance is termed as leakage reactance.

The inductance of the winding can be defined as:

$$L = \frac{N^2}{l/\mu_0 A_g} = \frac{(N^2 \mu_0 A_g)}{g} \tag{4.3}$$

Where $N$ - number of turns of the winding,

$l$ - the mean length of the magnetic circuit,

$\mu_0$ - the permeability,

$A_g$ - cross-sectional area of core.

The leakage reactance is:

$$X_{L=2\pi fL} \tag{4.4}$$

Where $f$ - the signal frequency,

$L$ - the inductance.

The magnitude of the leakage reactance depends on the number of turns of the winding, the leakage field, the current in the winding, and the geometry of the winding and core. The load current through the leakage reactance results in voltage drop. Leakage reactance is termed as percent leakage reactance. It is the ratio of the reactance voltage drop to the winding voltage multiplied by 100%.

To calculate the leakage reactance, first the inductance has to be calculated. Inductances for a single phase power transformer with the internal turn-to-turn fault were obtained using the Finite Element Analysis [41] - [42]. The parameters of a single phase transformer are given in Table A.5 in Appendix A. The calculation of the leakage reactance of a single phase transformer for different percentages of shorted turns on the primary and secondary windings is specified in Tables A.6 - A.7 in Appendix A.

## 4.3 Modeling differential relays in PSCAD

To protect three phase power transformers against internal turn-to-turn faults, the traditional transformer differential protection and the proposed method based on negative sequence currents are used. Models of both protection methods are described below.

### 4.3.1 Traditional differential protection method

To detect internal turn-to-turn faults the traditional protection relay can be used. The three phase differential relays have three single phase differential relays for each phase. Each differential relay has a differential component which has 2 elements:

- The restraint windings. Currents in the restraint windings tend to prevent tripping.
- The operating winding.

#### 4.3.1.1 The percentage differential slope

In the percentage differential relay, the differential current must exceed a fixed percentage of the through current in the transformer. The through current is referred to as the restraint current and is defined as the average of the primary and the secondary currents [9]:

$$I_r = \left(I_p + I_S \right) \cdot K \qquad (4.5)$$

Where $K$- a compensation factor, generally equals 0.5 or 1.

The relay will operate when the differential current ($I_d$) is greater than the restraining current ($I_r$):

$$I_d > SLP \cdot I_r \qquad (4.6)$$

Where $I_r$ - restraint current,

$SLP$ - the slope of the percentage differential characteristic is generally expressed as a percent value: typically 10%, 20%, and 40%.

A percentage slope $SLP$ of differential relay has been selected and adjusted to make the relay to be insensitive to mismatch between CT currents and relay tap setting, differences in accuracy of the CTs on either side of the transformer bank during faults, and to transformer tap changing (TTC). The slope of the percentage differential relay determines the trip zone.

The procedure of selecting the percentage differential slope (*SLP*) is [25]:

1. To calculate the rated currents at both voltage levels.
2. To select current transformers. For increased sensitivity, current transformer ratios have to be close to the rated current values as possible.
3. To calculate the current transformer secondary currents.
4. To calculate relay currents.
5. Select the relay taps that have a ratio as close as possible to the relay current ratio. Select $T_L$ and $T_{H.}$
6. To calculate the percentage of the current's mismatch to ensure that the relay taps selected have an adequate safety margin.

$$M = \left| \frac{\frac{I_L}{I_H} - \frac{T_L}{T_H}}{S} \right| * 100\% \tag{4.7}$$

Where $I_{L,}$ $I_H$ - relay input currents at the same kVA base for low and high voltage sides respectively.

$T_{L,}$ $T_H$ - relay tap settings for low and high voltage sides respectively.

$S$ - smaller of the two terms, $\frac{I_L}{I_H}$ or $\frac{T_L}{T_H}$.

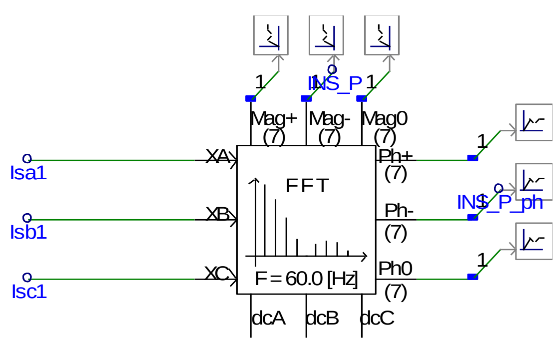
7. To calculate a difference in accuracy of the CT's on either side of the transformer bank.

To select the proper percentage slope for the relay characteristic when the information on unequal CT errors is not available, then an appropriate assumption can be made. It is reasonable to assume that the errors in the two CTs will not be more than 10% under all fault conditions. Therefore, the percentage differential slope for the relay can be selected including about 5% of safety margin.

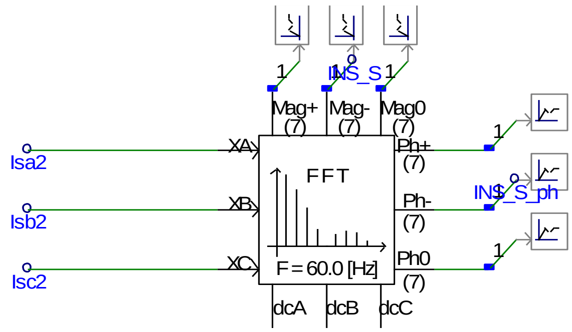
### 4.3.2 Description of the negative sequence currents' fault detection component

The new differential protection method works if the protected power transformer is connected to some load so that currents can flow on both sides of the protected power transformer. The proposed method based on negative sequence currents' has the negative sequence currents fault detection component.

The first step is to extract magnitudes of negative currents. To extract these magnitudes, the Fast Fourier Transform (FFT) block can be used. The FFT can determine the harmonic magnitude and phase of the input signal as a function of time. The FFT is a process of multiplying a signal by a sinusoid in order to determine frequency components of a signal. First the input signal is sampled before it is decomposed into harmonic constituents. The FFT provides the option of using one, two or three inputs. In the case of three inputs, the FFT block can take a three phase input and calculates the FFT output through a sequencer whose outputs are: positive (*Mag+*), negative (*Mag-*), and zero (*Mag0*) sequence magnitude components and positive (*Ph+*), negative (*Ph-*), and zero (*Ph0*) sequence phase components as shown in Figure 4.9.




(a) Primary side FFT block




(a) Secondary side FFT block

Figure 4.8 – Magnitudes and phase angles of sequence components produced by FFT blocks

Where $I_{SA1}$, $I_{SB1}$, $I_{SC1}$ - secondary phase currents produced by CT's on the primary side of TR in phase A, B, and C respectively,

$I_{SA2}$, $I_{SB2}$, $I_{SC2}$ - secondary phase currents produced by CT's on the secondary side of TR in phase A, B, and C respectively,

$I_{NS\_P}$ - magnitude of the negative sequence current on the primary side of TR scaled down using CT,

$I_{NS\_S}$ - magnitude of the negative sequence current on the secondary side of TR scaled down using CT,

$I_{NS\_P\_ph}$ - phase angle of the negative sequence current on the primary side of TR,

$I_{NS\_S\_ph}$ - phase angle of the negative sequence current on the secondary side of TR.

The second step is to check the magnitudes of the negative sequence currents from both sides of the transformer. As it was mentioned in Chapter 3, the magnitudes of negative sequence currents ($I_{NS\_P}$ and $I_{NS\_S}$) on both sides of the power transformer have to be higher than a pre-set level. The pre-set level was chosen to be 1%. The maximum current on the secondary side of the current transformer is 5 A. Therefore, 1% is 0.05 A. Magnitudes of negative sequence currents were extracted from the FFT blocks.

To compare magnitudes of negative sequence currents with a pre-set level, a comparator has been used. This component compares two inputs. The output from the comparator is a level output which is obtained when one signal is above the other signal. The comparison of negative sequence currents with a pre-set level using the comparator is depicted in Figure 4.9.

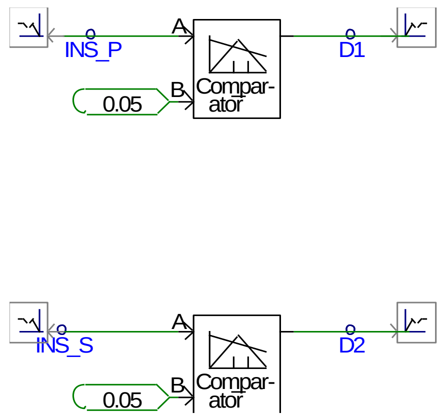



Figure 4.9 – Comparison of negative sequence currents with a pre-set level

Second, if the contribution of negative sequence currents from both sides of the transformer is less than a pre-set level, then a directional comparison is not done to avoid the possibility of making a wrong decision.

But if the contribution of negative sequence currents from both sides of the power transformer is more than a pre-set level, then a directional comparison can be done and a phase angle between two phasors of negative sequence currents can be found.

If outputs ($D_1$ and $D_2$) from both comparators are 1, which means that both magnitudes of negative sequence currents are greater than a pre-set level, then a phase angle between two negative sequence currents can be checked. Phase angle comparison between two phasors of negative sequence currents is shown in Figure 4.10.

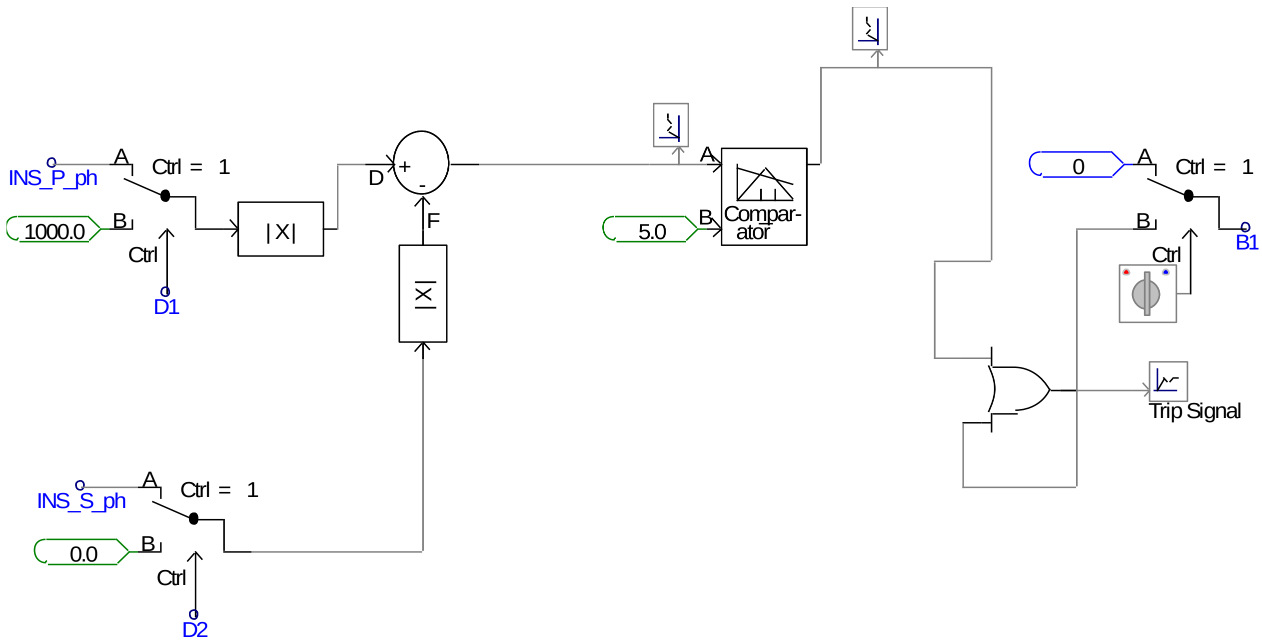



Figure 4.10 – Phase angle comparison between two phasors of negative sequence currents

As it is shown in Figure 4.10, two 2 input selectors have been used in phase angle comparison. The output from the selector will be A or B depending on the value of Ctrl. If the value of Ctrl is 1, then the output of the selector 1 will be $I_{NS\_P\_ph}$, and if the value of Ctrl of the selector 2 is 1, then the output will be $I_{NS\_S\_ph}$. Then using the Summing/Differencing Junctions block, the difference between these two angles can be found. If the difference is in the range between 0-5 degrees, then an internal fault is indicated and a trip command is issued.

## 4.4 Summary

This chapter gives a detailed description of the components of the modelled power system under study. Also, models of the traditional differential protection and the proposed technique based on negative sequence currents are presented in this chapter. The PSCAD/EMTDC software (version 4.2.1) is used to model the power system and design the traditional differential relay model and the differential relay based on negative sequence currents' models. The model of the proposed relay based on negative sequence currents has the negative sequence currents' fault detection component. The operation of the negative sequence currents' fault detection component is described.

# CHAPTER 5
# TEST RESULTS

## 5.1 Introduction

This chapter presents the test results using the protection method based on negative sequence currents and the traditional differential protection method. The purpose of these studies is to detect minor internal turn-to-turn faults within the power transformer using both methods and compare their performance for various cases.

## 5.2 Performance of the traditional differential protection

The purpose of this study is to investigate the performance of the traditional differential protection for internal turn-to-turn faults. The transformer winding fault is the most difficult fault to detect within the power transformer. The most difficult aspect of it is providing power transformer protection when only a few turns are shorted. As it is known, the changes in magnitude of the transformer’s terminal currents are very small when a limited number of turns are shorted within the power transformer. IEEE Standard indicates that at least 10% of the transformer winding has to be shorted to cause detectable change in the terminal current. Therefore, when fewer numbers of turns are shorted, it will result in an undetectable amount of current [5].

The first step is to investigate how accurately the traditional differential protection can detect minor internal turn-to-turn faults. The internal turn-to-turn fault occurred on the secondary winding (HV side) in phase C of the power transformer as depicted in Figure 5.1. The time taken to apply the fault is 3 seconds with duration of 0.4 seconds. In this study, the restraint characteristic has been set to 20%.

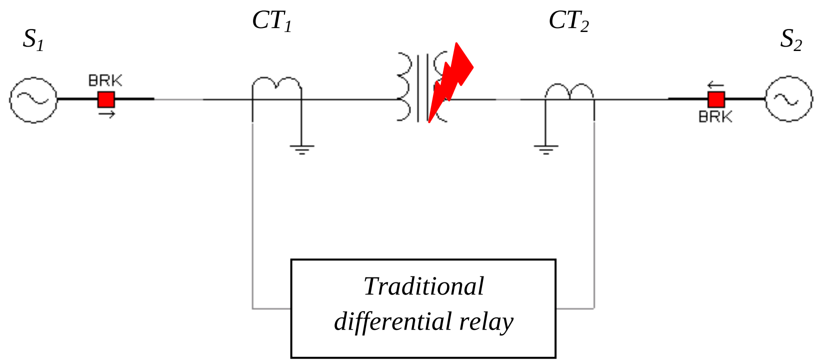
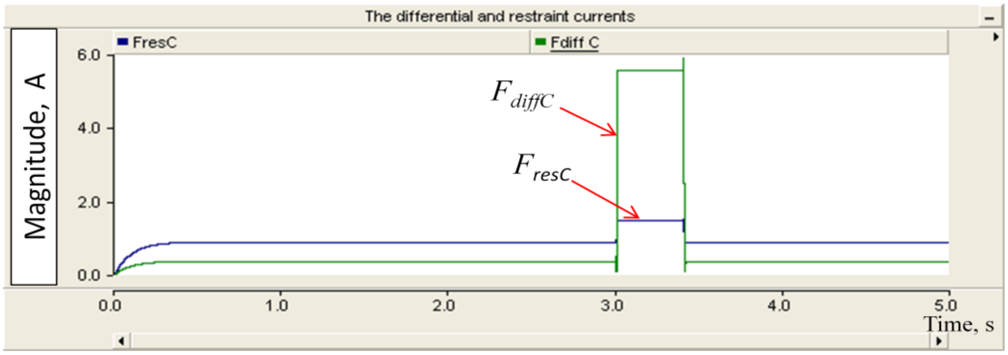



Figure 5.1 – Internal turn-to-turn fault on the secondary winding of the power transformer

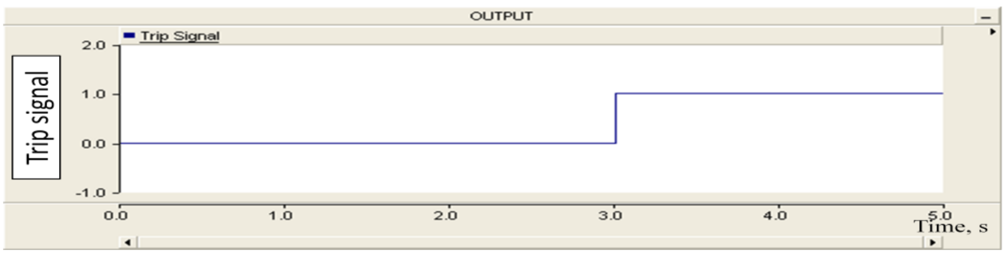
### 5.2.1 Differential current versus restraining current

The next sets of figures show the differential and restraining currents of the traditional differential protection for an internal turn-to-turn fault for various percentages of shorted turns on the secondary winding in phase C of the power transformer and trip signals from the relay.

Figures 5.2 - 5.4 show that the differential current ($F_{diffC}$) remains above the value of the restraining current ($F_{resC}$) which means that the traditional differential relay will operate for internal turn-to-turn faults when a higher number of turns (for example 25%, 15%, and 10% of turns) are shorted.

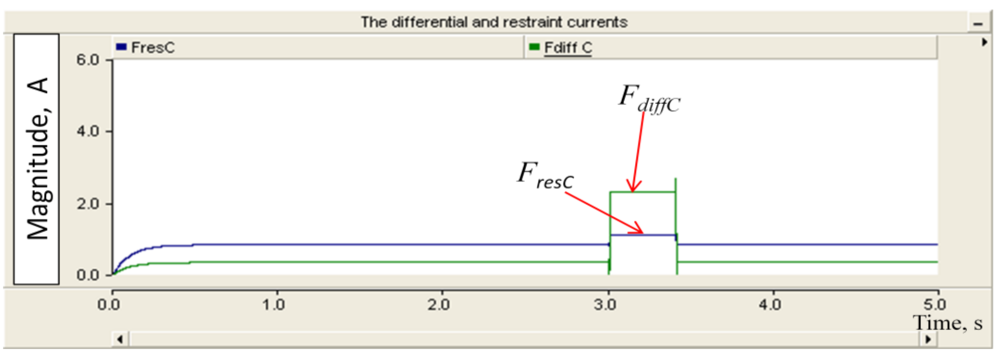



(a) Differential and restraining current

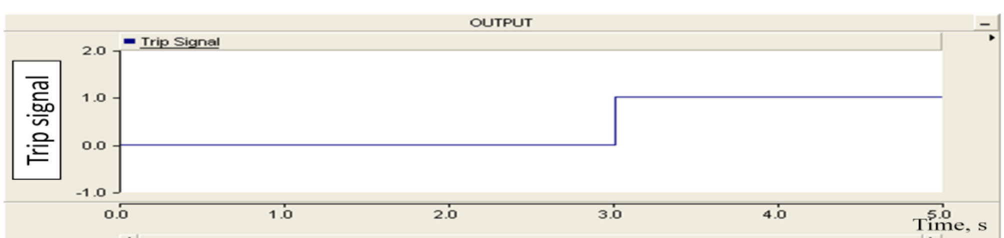



(b) Trip signal

Figure 5.2 – Traditional differential relay response when **25%** of turns are shorted

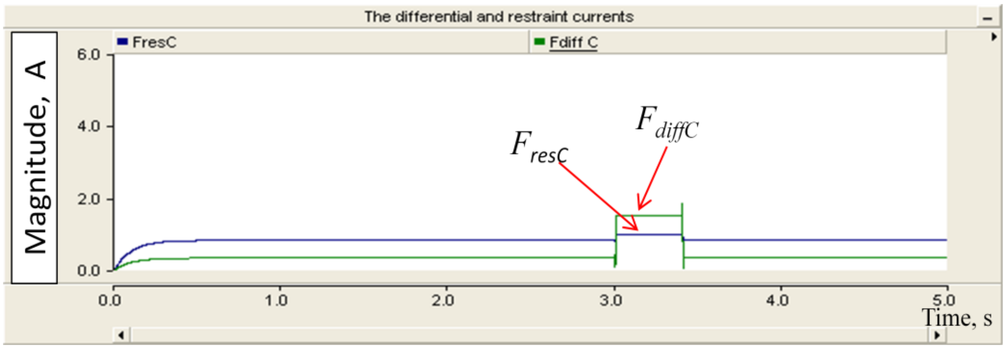



(a) Differential and restraining current

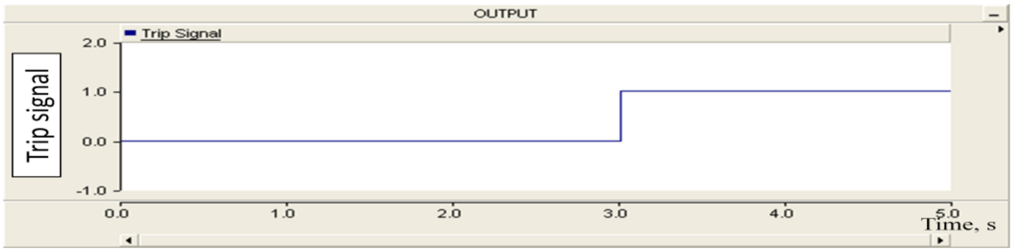



(b) Trip signal

Figure 5.3 – Traditional differential relay response when **15%** of turns are shorted




(a) Differential and restraining current

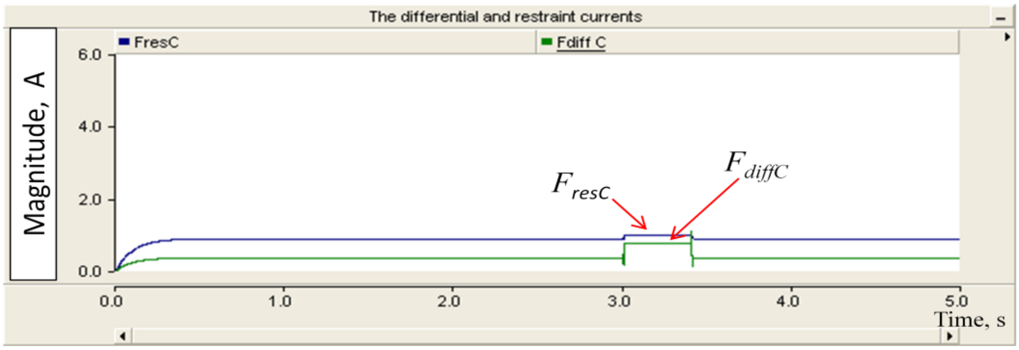



(b) Trip signal

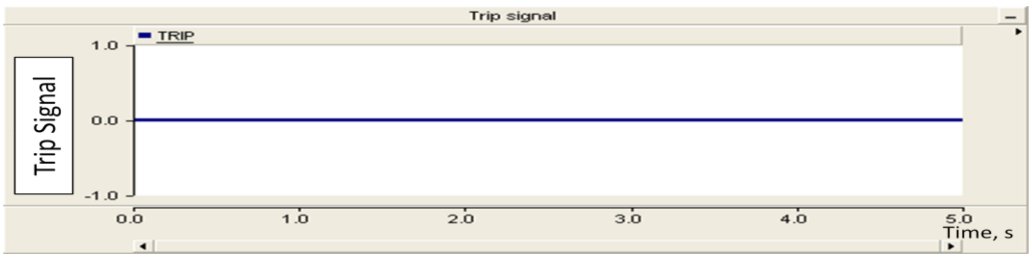
Figure 5.4 – Traditional differential relay response when **10%** of turns are shorted

Figures 5.5 - 5.7 show that the restraining current ($F_{resC}$) remains above the value of the differential ($F_{diffC}$) current which means that the traditional differential relay does not operate for internal turn-to-turn faults when a small number of the turns are shorted (for example 5%, 3%, and 1% of turns are shorted on the secondary winding of the power transformer). The restraint characteristic has been set to 20% and a minor internal turn-to-turn fault when 5%, 3%, and 1% of turns are shorted causes a differential current to be less than 20%. For this reason, the traditional differential protection cannot detect a turn-to-turn fault for these three cases with small number of turns shorted.

The results in Figures 5.5 - 5.7 are in agreement with the IEEE Standard which states that at least 10% of turns have to be shorted in order to detect internal turn-to-turn faults.

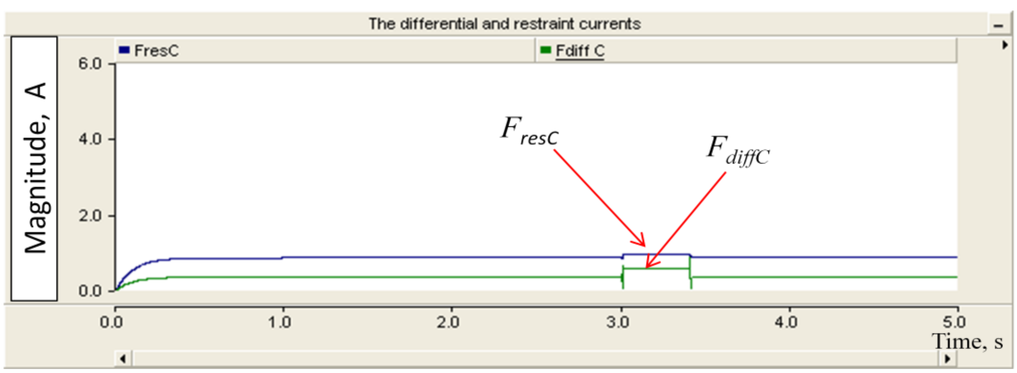



(a) Differential and restraining current

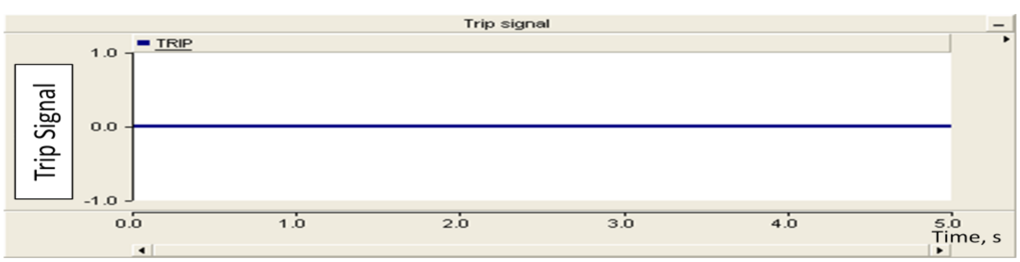



(b)Trip signal

Figure 5.5 – Traditional differential relay response when **5%** of turns are shorted

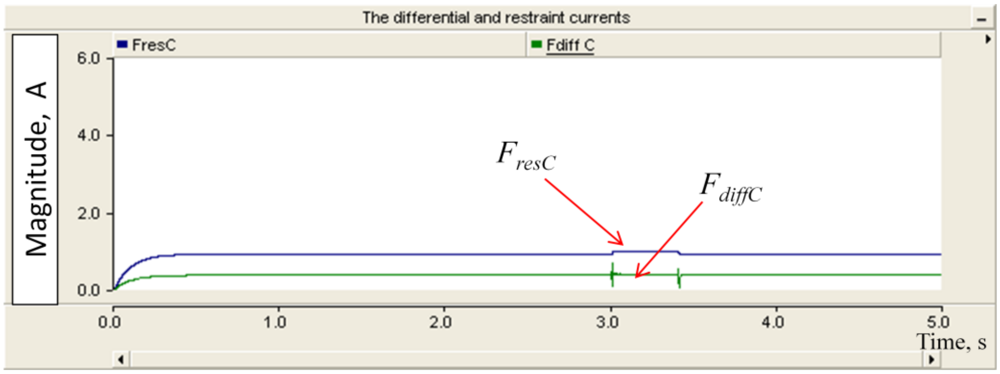



(a) Differential and restraining current

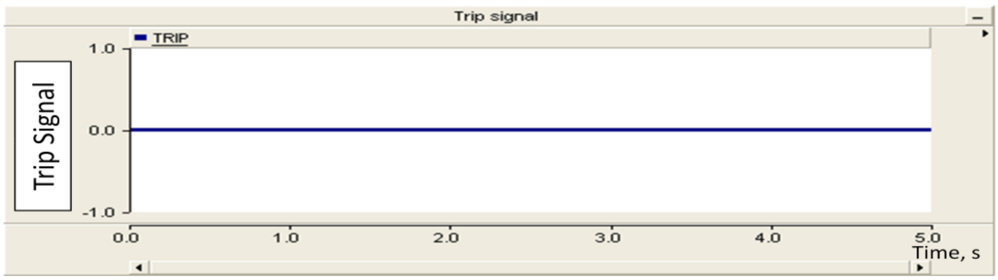



(b) Trip signal

Figure 5.6 – Traditional differential relay response when **3%** of turns are shorted




(a) Differential and restraining current




(b) Trip signal

Figure 5.7 – Traditional differential relay response when **1%** of turns are shorted

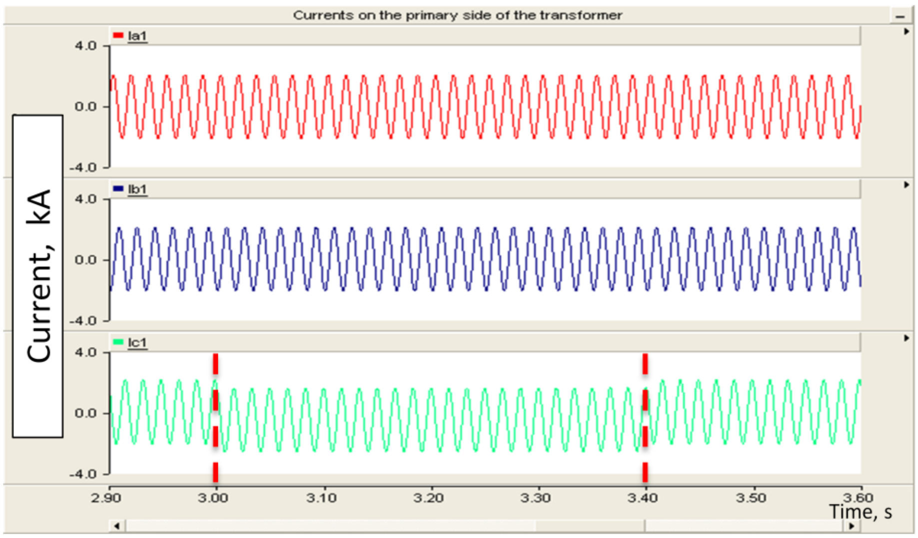
The above results show that the transformer protection requires a new sensitive method to detect minor internal turn-to-turn faults (especially when less than 10% of turns are shorted).

### 5.2.2 Primary and secondary phase currents during internal turn-to-turn faults

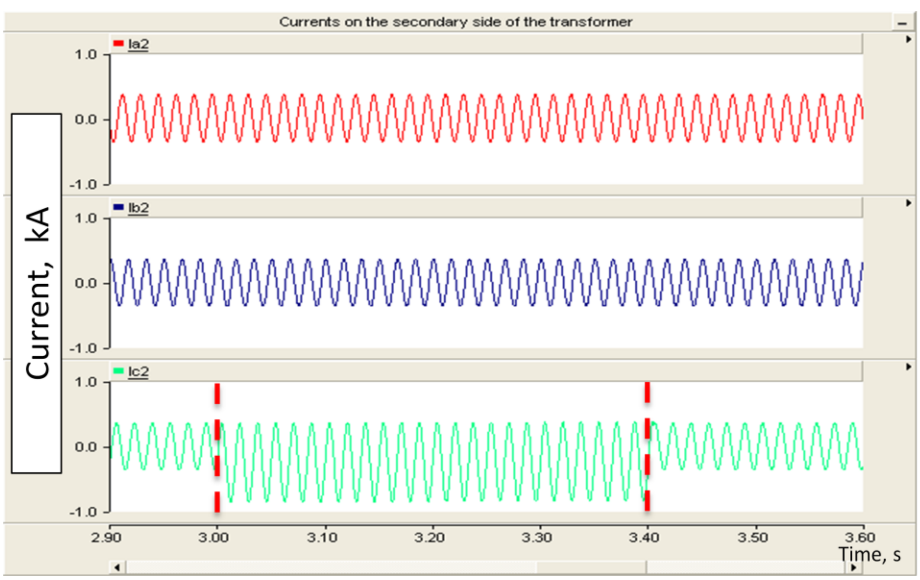
The traditional differential protection is not sensitive enough to detect minor internal turn-to-turn faults within the power transformers because the changes in the transformer's terminal current are quite small and the ratio of transformation between the whole winding and the short-circuited turns is quite small.

The next sets of figures show phase currents on the primary side ($I_{a1}$, $I_{b1}$, $I_{c1}$) of the power transformer and on the secondary side ($I_{a2}$, $I_{b2}$, $I_{c2}$) during the internal turn-to-turn fault on the secondary winding in phase C for various percentages of shorted turns.

As it can be seen from Figures 5.8 - 5.10, the changes in the transformer terminal's current in phase C due to the internal turn-to-turn fault when 25%, 15%, and 10% of turns are shorted on the secondary winding, are sufficiently large enough.  Because these changes are sufficiently large enough, the traditional differential protection can detect the internal turn-to-turn fault for these cases.

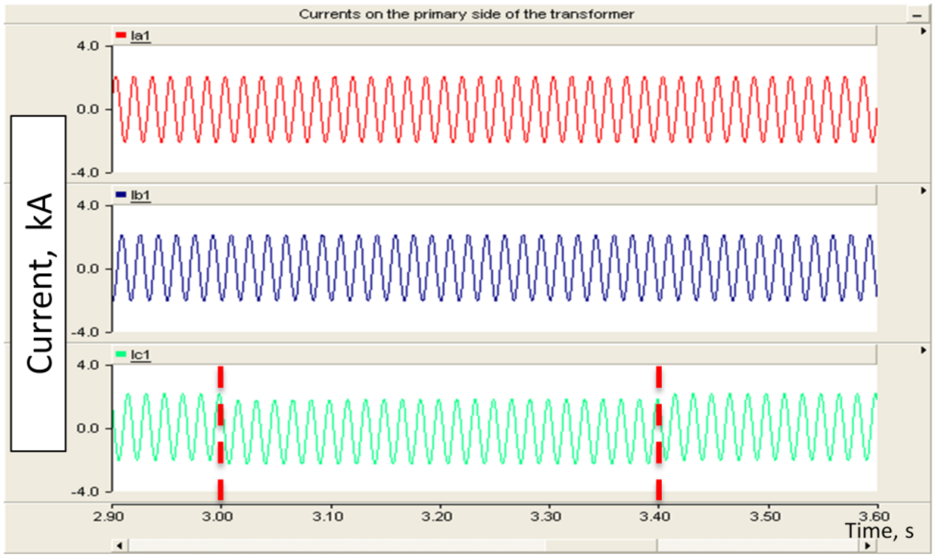



(a) Primary side of the power transformer

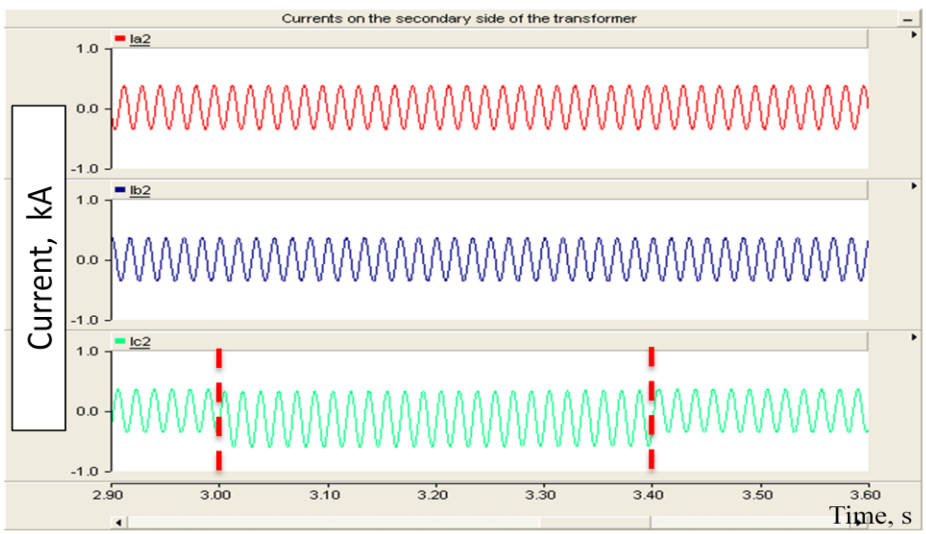



(b) Secondary side of the power transformer

Figure 5.8 – Phase currents on both sides when **25%** of turns are shorted

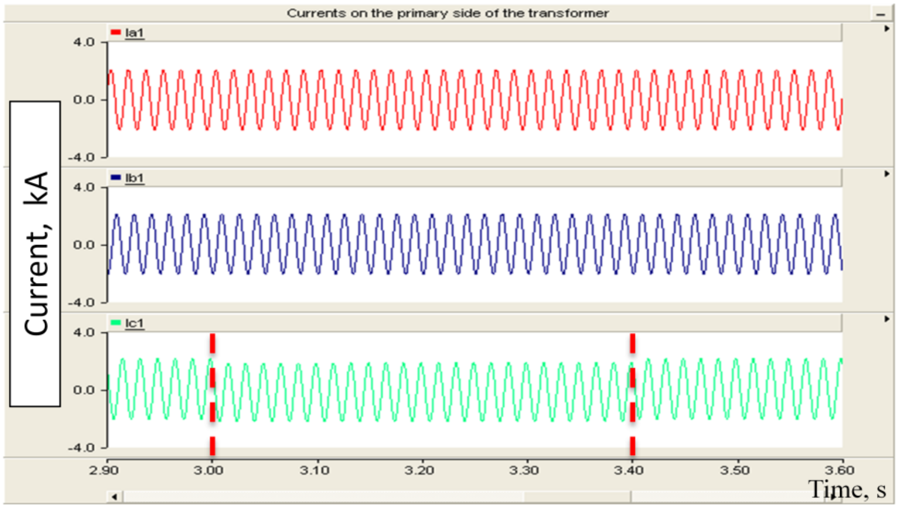



(a) Primary side of the power transformer

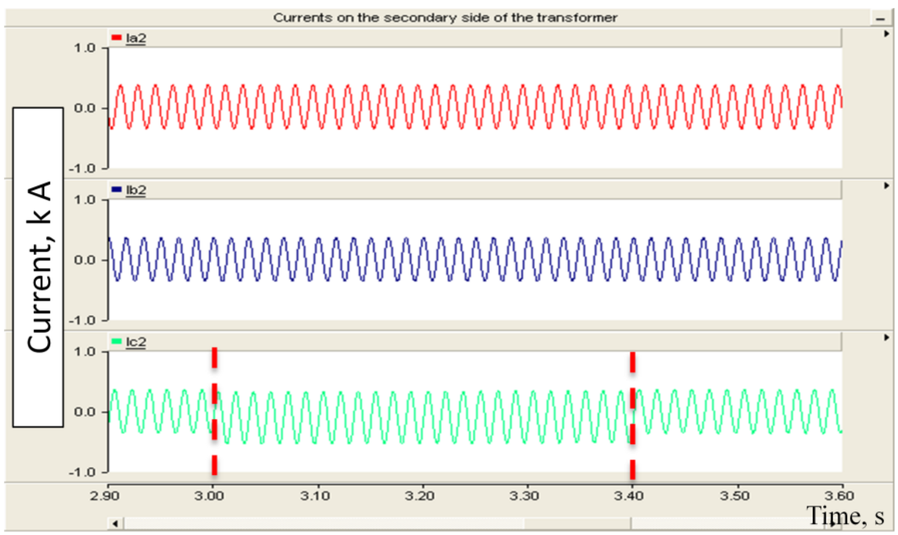



(b) Secondary side of the power transformer

Figure 5.9 – Phase currents on both sides when **15%** turns are shorted



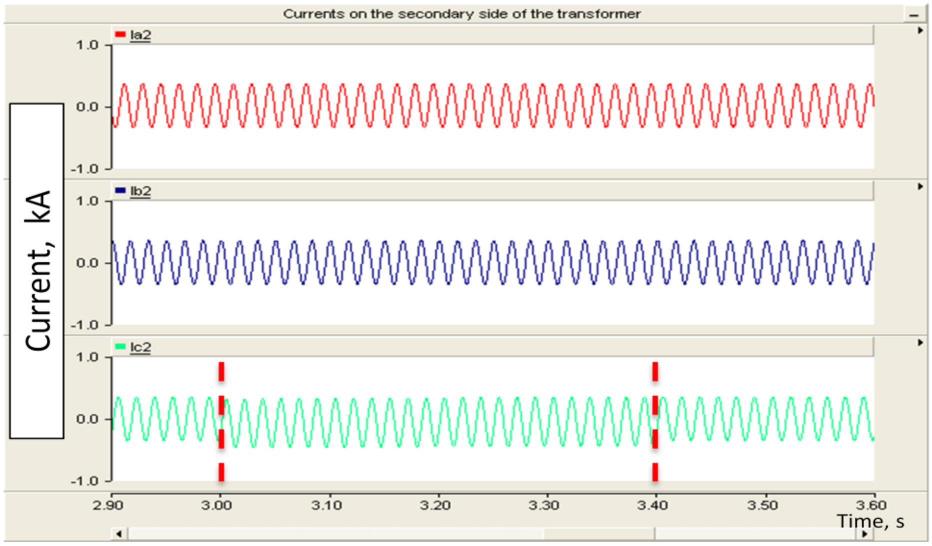

(a) Primary side of the power transformer



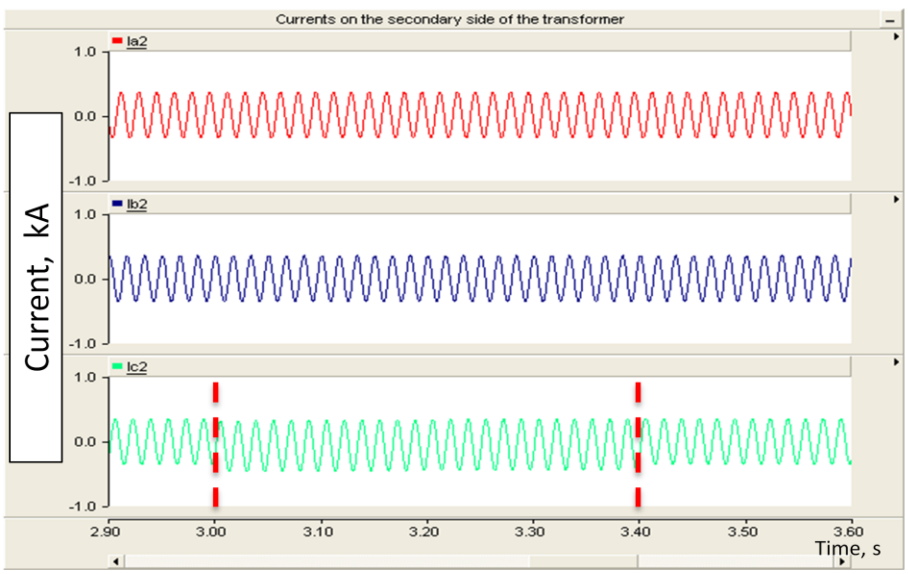

(b) Secondary side of the power transformer

Figure 5.10 – Phase currents on both sides when **10%** of turns are shorted

Figures 5.11 - 5.13 show that the changes in the transformer terminal's current due to the internal turn-to-turn fault in phase C in the power transformer are quite small when less turns are shorted. As it can be seen, the transformer terminal's current in phase C during the internal turn-to-turn faults is almost the same as the current during normal operation. The results shown above further demonstrate that it is difficult to detect minor internal turn-to-turn faults using the traditional differential protection.

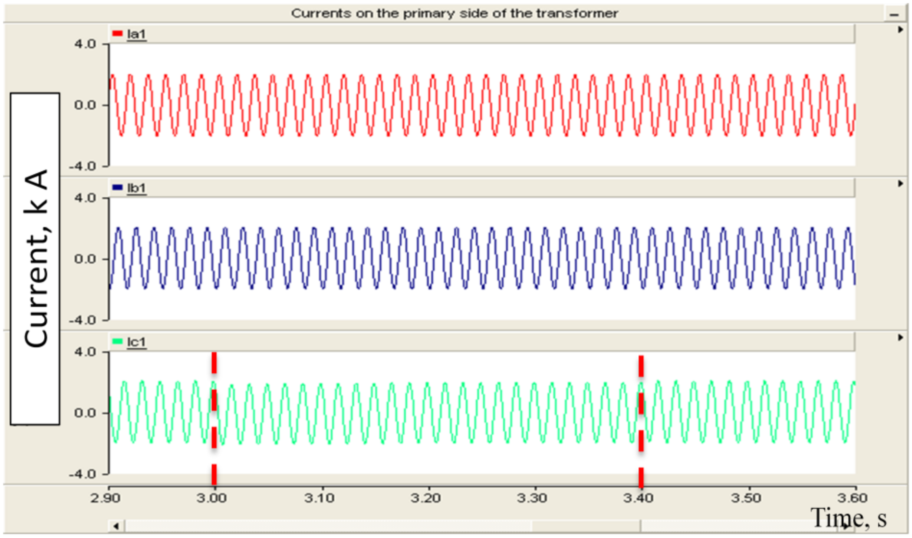



(a) Primary side of the power transformer

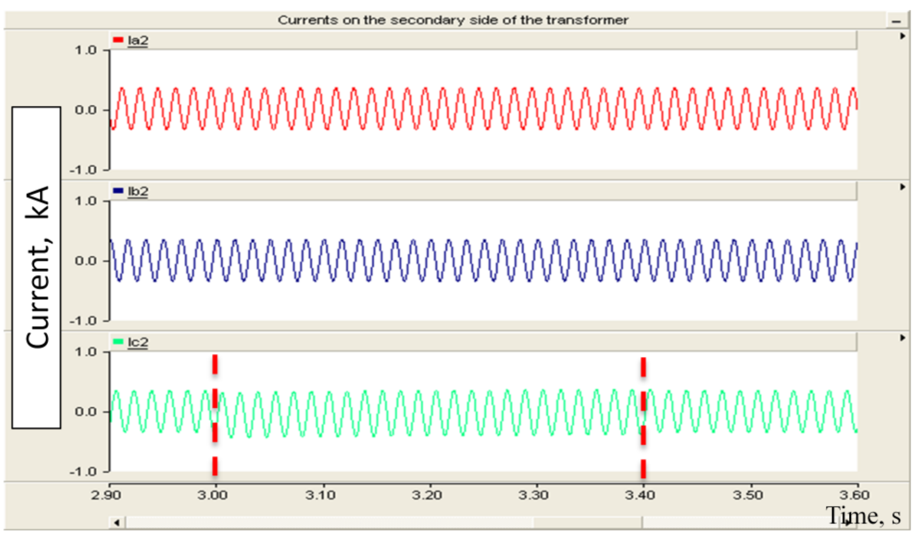



(b) Secondary side of the power transformer

Figure 5.11 – Phase currents on both sides when **5%** of turns are shorted

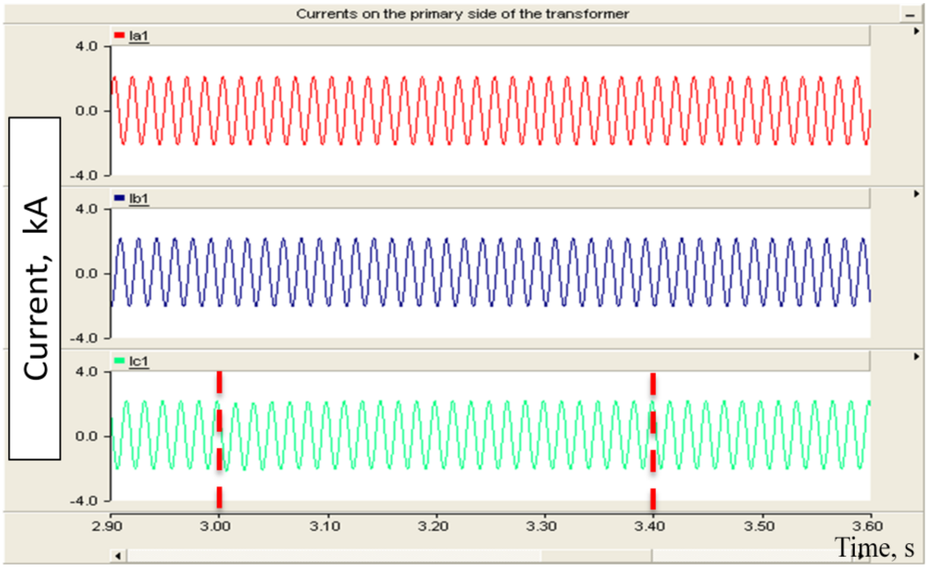



(a) Primary side of the power transformer

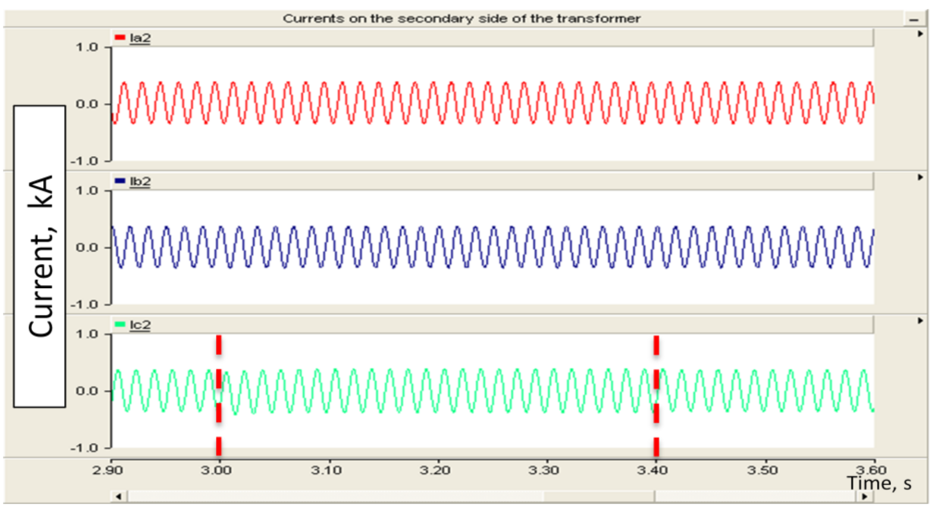



(b) Secondary side of the power transformer

Figure 5.12 – Phase currents on both sides when **3%** of turns are shorted




(a) Primary side of the power transformer




(b) Secondary side of the power transformer

Figure 5.13 – Phase currents on both sides when **1%** of turns are shorted

## 5.3 Performance of the proposed method for internal turn-to-turn faults

The purpose of these studies is to demonstrate the effectiveness of the protection technique, which is based on negative sequence currents for detecting minor internal turn-to-turn faults in power transformers.

In this section the results obtained from the negative sequence currents based protection method are organized under the following subsections:

a. Different number of shorted turns of the power transformer.
b. Different values of the fault resistances.
c. Different values of the system parameters.
d. Different connections of the power transformer.
e. CT saturation.
f. Inrush current.

Performance of the proposed method based on negative sequence currents will also be compared with the performance of the traditional differential protection method.

### 5.3.1 Turn-to-turn faults on the secondary winding of the power transformer connected in Y-Y

In this study, an internal turn-to-turn fault occurred on the secondary winding (HV side) in phase C of the power transformer connected in Y-Y. The time taken to apply the fault is 3 seconds with duration of 0.4 seconds. The total number of the turns on the secondary winding is 866 turns.

The negative sequence currents are going to be present on both sides of the power transformer with different magnitudes. Figures 5.14 - 5.19 show the magnitude of the negative sequence current on the primary side ($I_{NS\_P}$) and the magnitude of the negative sequence current on the secondary side ($I_{NS\_S}$) for different percentages of shorted turns. The magnitude of the negative sequence current on the faulty side ($I_{NS\_S}$) is greater than the magnitude of the negative sequence current on the other side ($I_{NS\_P}$) as expected.

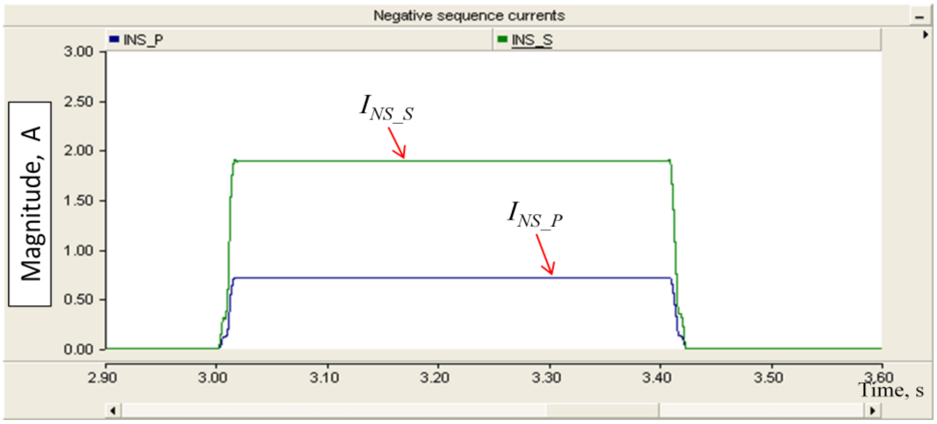



Figure 5.14 – Negative sequence current magnitudes for **25%** shorted turns on secondary (Y-Y)

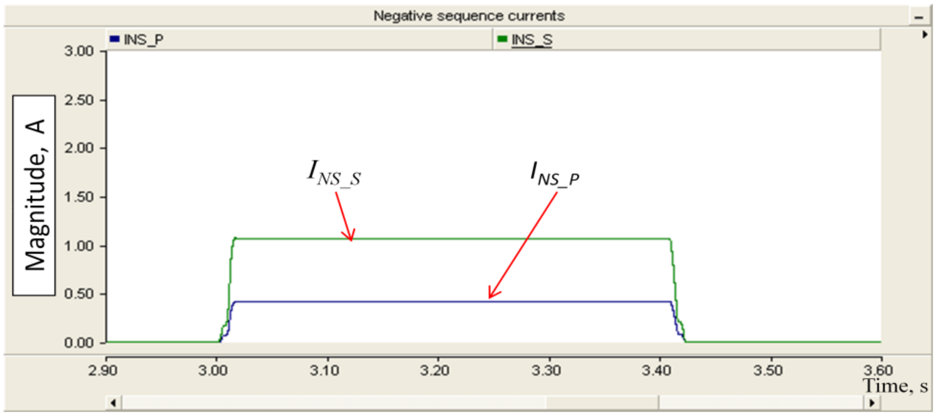



Figure 5.15 – Negative sequence current magnitudes for **15%** shorted turns on secondary (Y-Y)

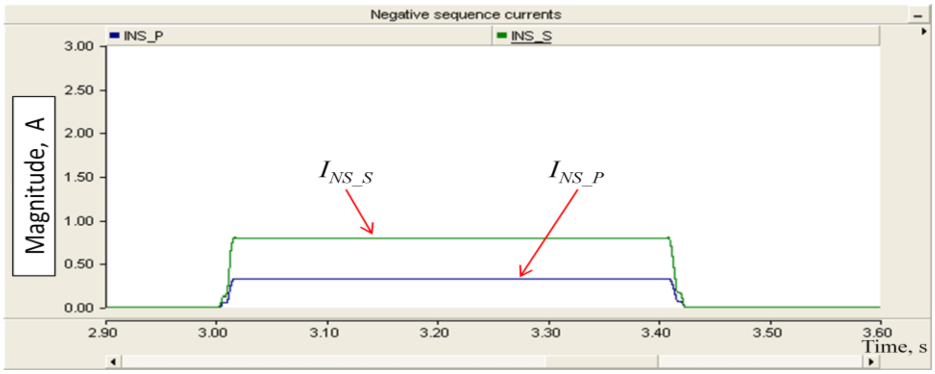



Figure 5.16 – Negative sequence current magnitudes for **10%** shorted turns on secondary (Y-Y)

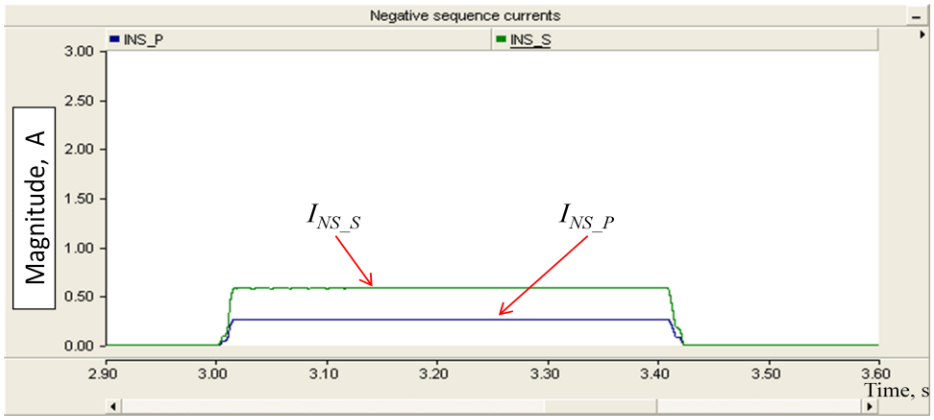



Figure 5.17 – Negative sequence current magnitudes for **5%** shorted turns on secondary (Y-Y)

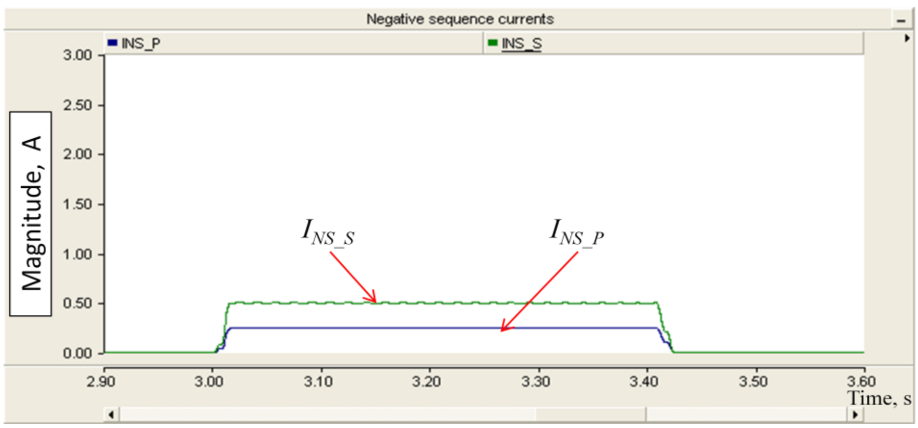



Figure 5.18 – Negative sequence current magnitudes for **3%** shorted turns on secondary (Y-Y)

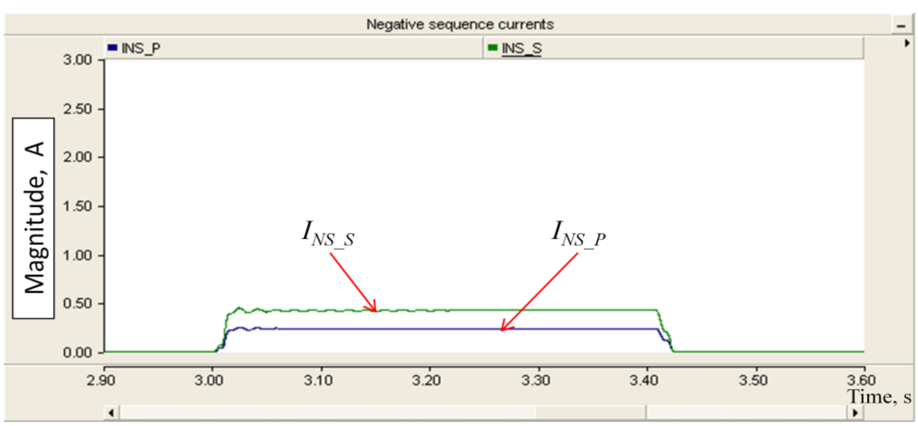



Figure 5.19 – Negative sequence current magnitudes for **1%** shorted turns on secondary (Y-Y)

Figures 5.20 - 5.25 show 'zooming in' on the magnitudes of the two components of the total negative sequence current for various percentages of shorted turns. Magnitudes of negative sequence currents are compared with a pre-set level which is 1 % (0.05 A) of the differential protection's base current.

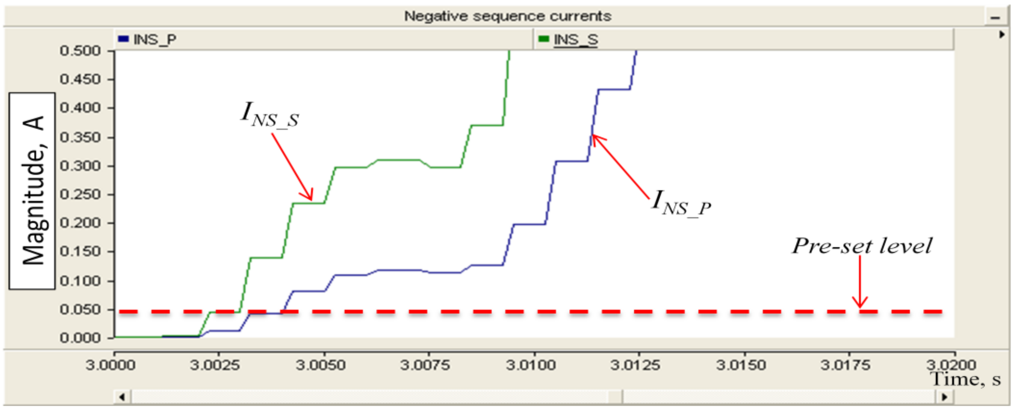



Figure 5.20 – Zooming in on negative sequence current magnitudes for **25%** shorted turns on secondary (Y-Y)

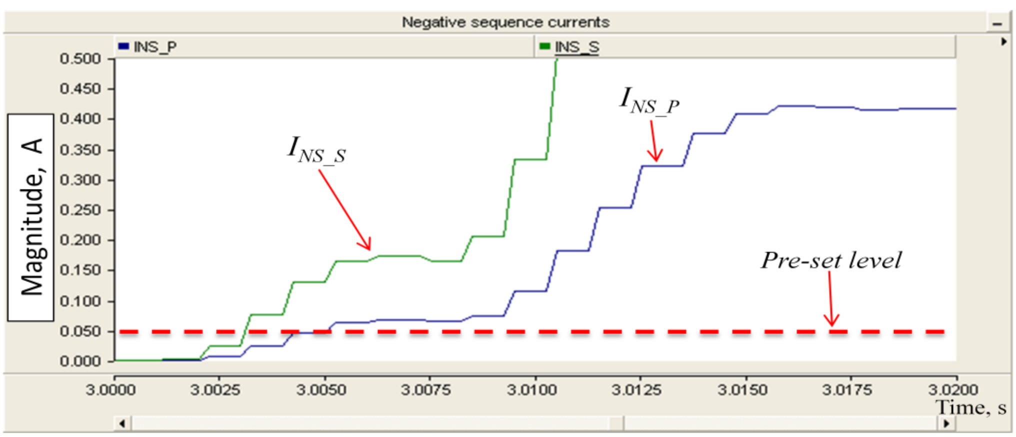



Figure 5.21 – Zooming in on negative sequence current magnitudes for **15%** shorted turns on secondary (Y-Y)

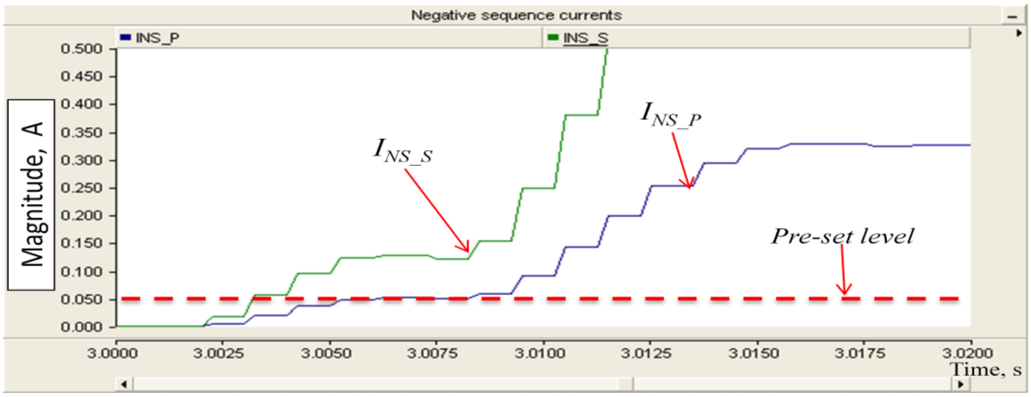



Figure 5.22 – Zooming in on negative sequence current magnitudes for **10%** shorted turns on secondary (Y-Y)

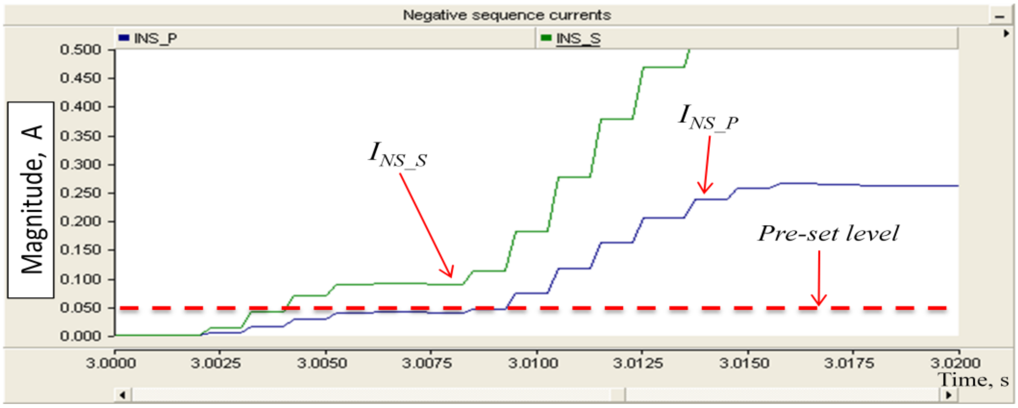



Figure 5.23 – Zooming in on negative sequence current magnitudes for **5%** shorted turns on secondary (Y-Y)

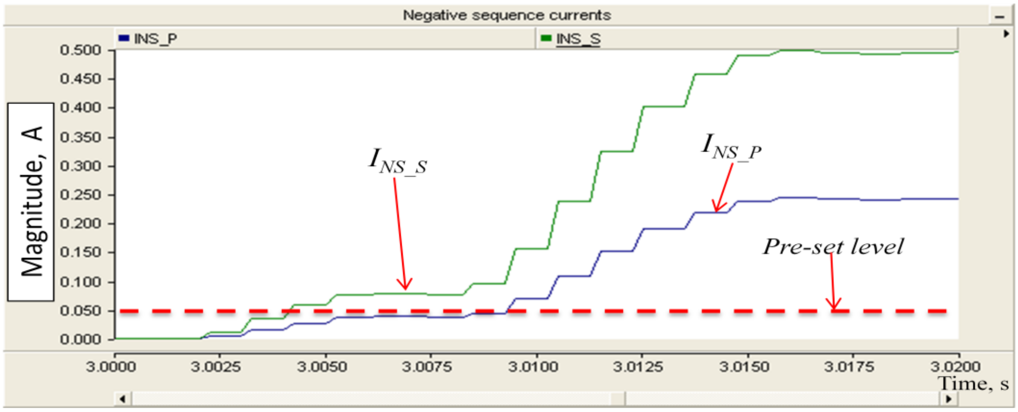



Figure 5.24 – Zooming in on negative sequence current magnitudes for **3%** shorted turns on secondary (Y-Y)

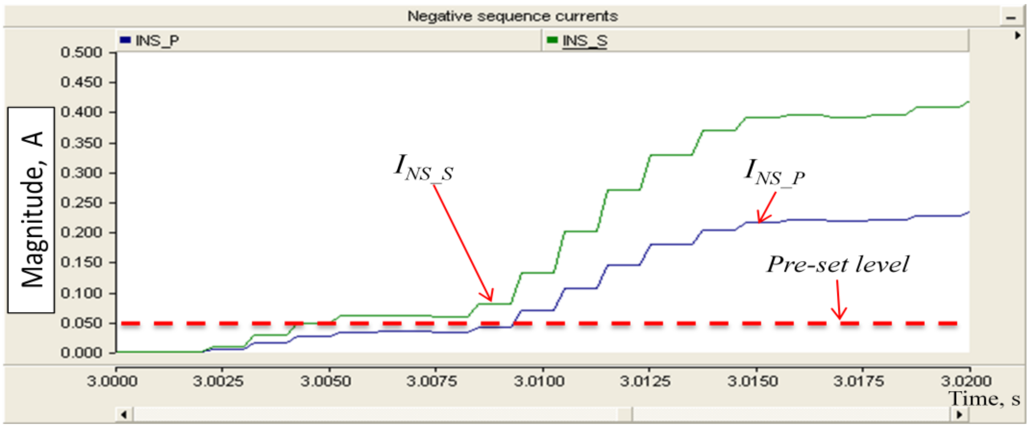



Figure 5.25 – Zooming in on negative sequence currents magnitudes for **1%** shorted turns on secondary (Y-Y)

Figures 5.26 - 5.31 show the relative phase angle between two phasors of negative sequence currents during the internal turn-to-turn fault, which represent the respective contribution.

Theoretically, the phase angle between two phasors of negative sequence currents has to be 0 degrees, but in reality there are some other arbitrary phase angle shift caused by the quite high current in the shorted turns. For the modelled power system, the phase angle shift between two phasors of negative sequence currents is set from 0 to 5 degrees in order to ensure a very sensitive turn-to-turn fault detection.

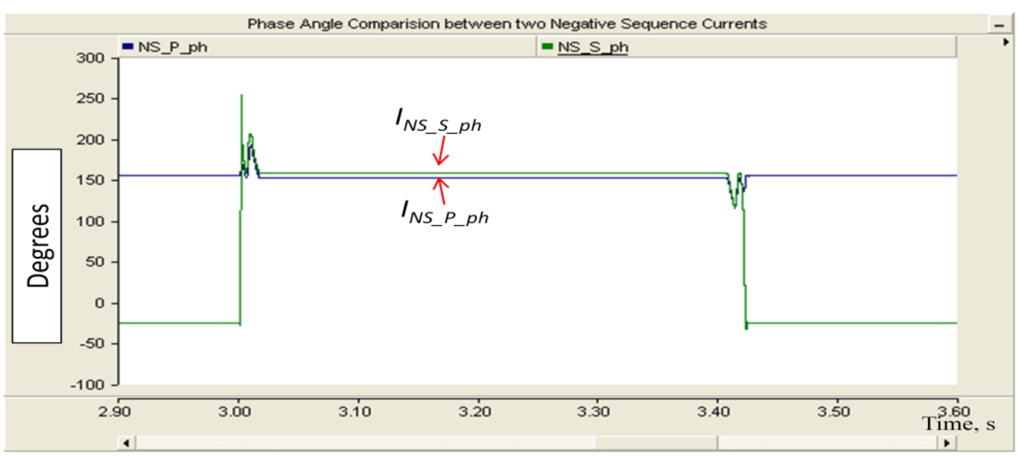



Figure 5.26 – Phase angle comparison between two negative sequence currents for **25%** shorted turns on the secondary (Y-Y)

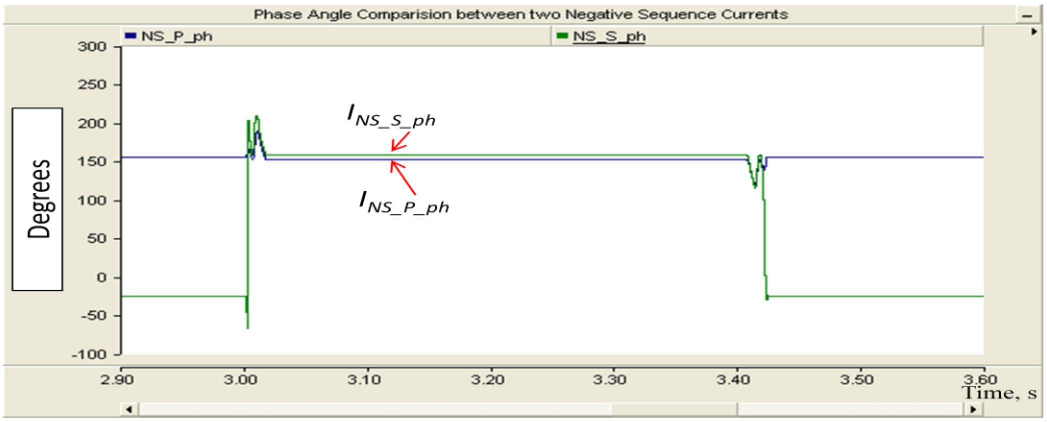



Figure 5.27 – Phase angle comparison between two negative sequence currents for **15%** shorted turns on secondary (Y-Y)

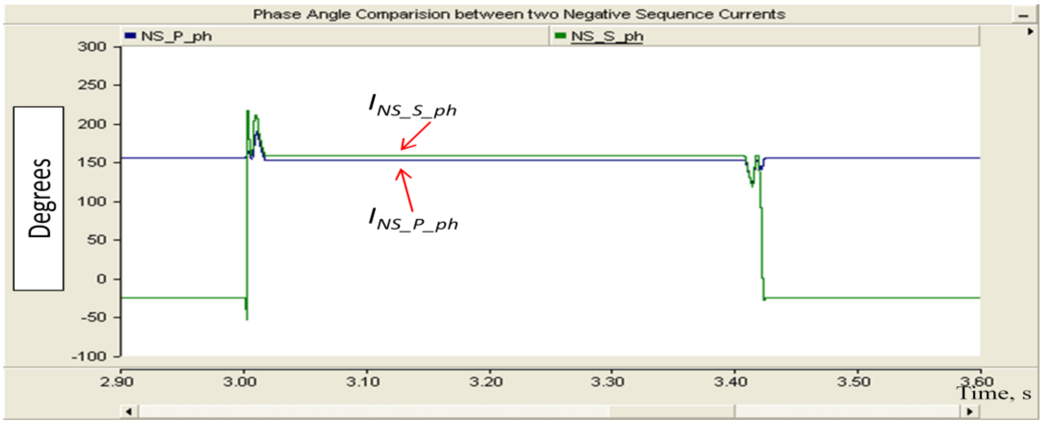



Figure 5.28 – Phase angle comparison between two negative sequence currents for **10%** shorted turns on secondary (Y-Y)

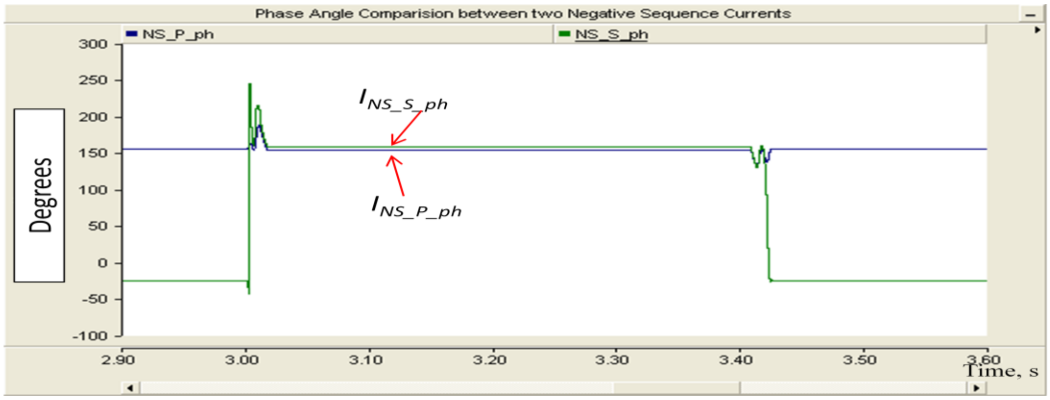



Figure 5.29 – Phase angle comparison between two negative sequence currents for **5%** shorted turns on secondary (Y-Y)

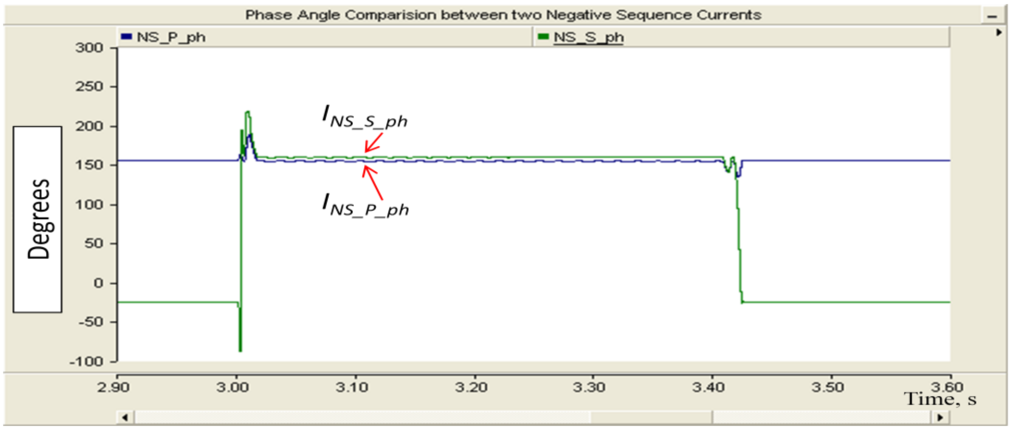



Figure 5.30 – Phase angle comparison between two negative sequence currents for **3%** shorted turns on secondary (Y-Y)

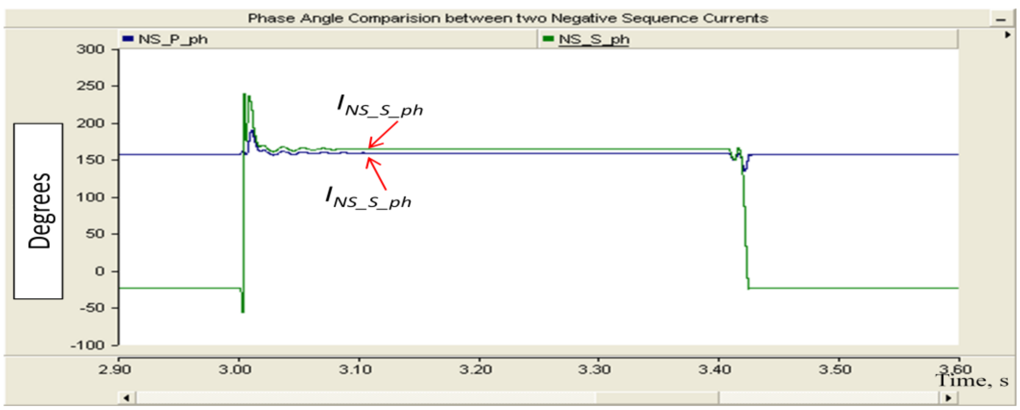



Figure 5.31 – Phase angle comparison between two negative sequence currents for **1%** shorted turns on secondary (Y-Y)

Figures 5.32 - 5.37 show output signals from the proposed technique based on negative sequence currents for different percentages of shorted turns on the secondary winding of the power transformer. It can be seen from these figures that the proposed method can detect minor internal turn-to-turn faults as low as 1% (8 turns) of shorted turns on the secondary winding in phase C. A turn-to-turn fault for different percentages of shorted turns was detected within one cycle (0.16 seconds).

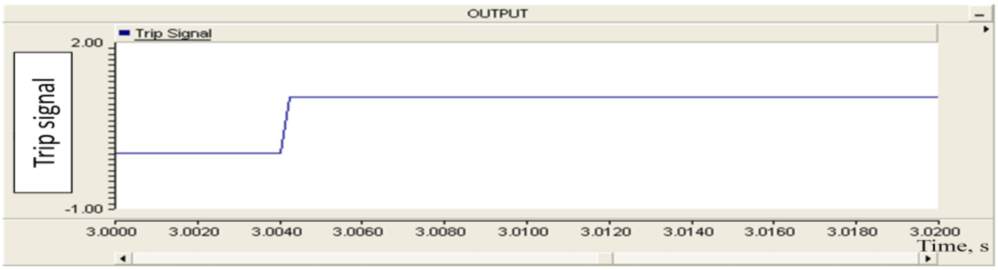



Figure 5.32 – Trip signal from the proposed relay for **25%** shorted turns on secondary (Y-Y)

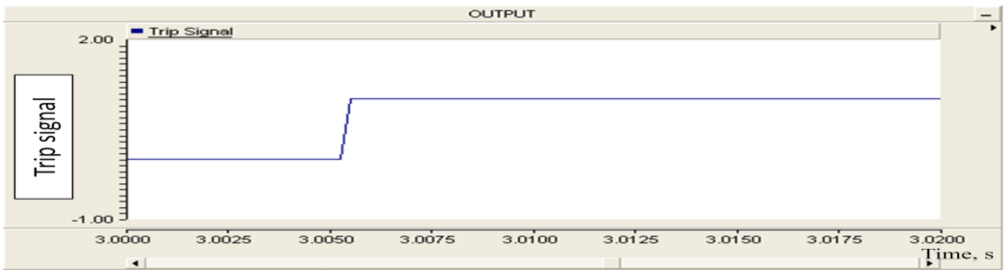



Figure 5.33 –Trip signal from the proposed relay for **15%** shorted turns on secondary (Y-Y)

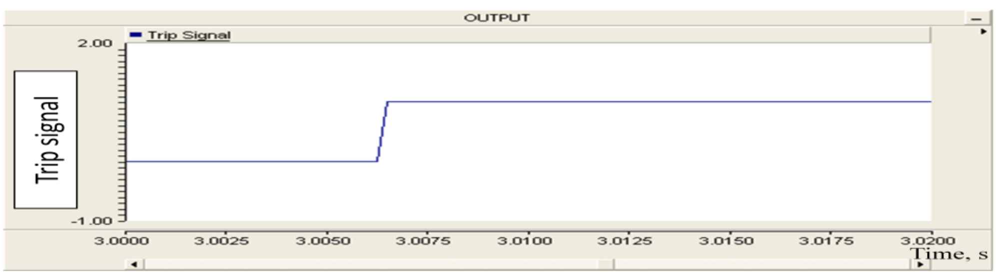



Figure 5.34 – Trip signal from the proposed relay for **10%** shorted turns on secondary (Y-Y)

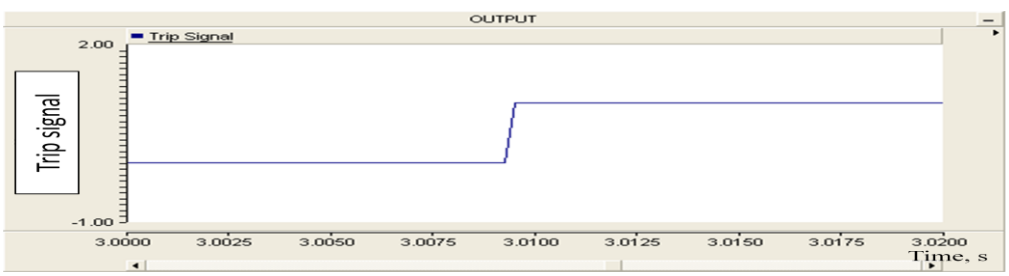



Figure 5.35 – Trip signal from the proposed relay for **5%** shorted turns on secondary (Y-Y)

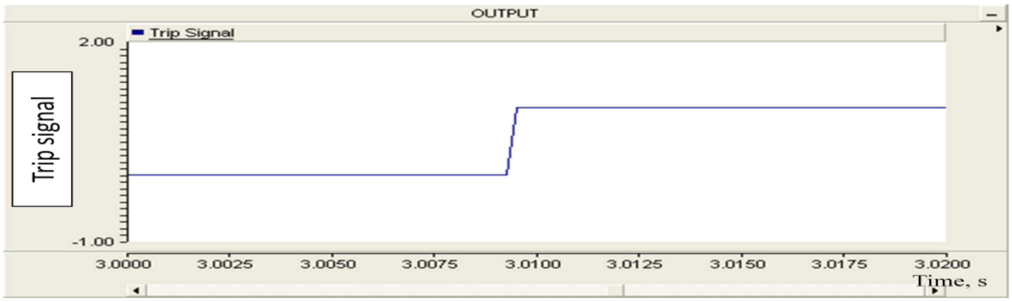



Figure 5.36 – Trip signal from the proposed relay for **3%** shorted turns on secondary (Y-Y)

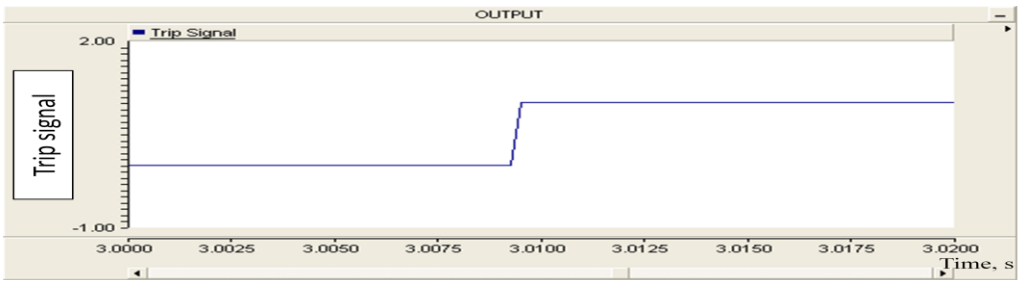



Figure 5.37 – Trip signal from the proposed relay for **1%** shorted turns on secondary (Y-Y)

### 5.3.1.1 Sensitivity analysis of the proposed relay for turn-to-turn faults on the secondary winding (Y-Y)

**1. Effect of the fault resistance**

The fault resistance is associated with the fault impedance path. The fault resistance may affect the performance of the proposed technique based on negative sequence currents and result in unreliable response of the relay. It should be noted that if a turn-to-turn fault involves a fault resistance, then the sensitivity of the proposed technique is going to be reduced, but it should also be noted that the fault resistance is going to have the same effect even on a traditional differential protection.

Table 5.1 gives the values of the negative sequence currents on the primary and secondary windings of the power transformer for a bolted turn-to-turn fault ($R_f = 0\Omega$) which were obtained from simulation. As it can be seen from Table 5.1, the proposed technique based on negative sequence currents is sensitive in detecting a turn-to-turn fault for a bolted turn-to-turn fault for all cases.

Table 5.1 – Turn-to-turn fault on the secondary winding of the power transformer connected in Y- Y for various percentages of shored turns ($R_f = 0\Omega$)

| *Shorted turns, %* | $I_{NS\_P}$, *A* | $I_{NS\_S}$, *A* | *Output signal* | |
|---|---|---|---|---|
| | | | *Trip action* | *Trip time, ms* |
| 25 | 0.708 | 1.883 | Trip | 4 |
| 15 | 0.415 | 1.058 | Trip | 5.24 |
| 10 | 0.328 | 0.790 | Trip | 6.25 |
| 5 | 0.262 | 0.577 | Trip | 9 |
| 3 | 0.242 | 0.496 | Trip | 9.30 |
| 1 | 0.234 | 0.421 | Trip | 9.30 |

Faults are seldom solid and involve a varying amount of resistance. For the purpose of testing a protective technique it is usually assumed that a small resistance is involved. Therefore, to make the studies more realistic, a fault resistance $R_f = 1\Omega$ was included in the studies shown next.

Table 5.2 gives the measured values of the negative sequence currents on the primary and secondary windings of the power transformer for the arcing turn-to-turn fault with the fault resistance of 1 $\Omega$. As it can be seen from Table 5.2, the sensitivity of the proposed technique is reduced.

Table 5.2 – Turn-to-turn fault on the secondary winding of the power transformer connected in Y-Y for various percentages of shored turns ($R_f = 1\Omega$)

| *Shorted turns, %* | $I_{NS\_P}$, *A* | $I_{NS\_S}$, *A* | *Output signal* | |
|---|---|---|---|---|
| | | | *Trip action* | *Trip time, ms* |
| 25 | 0.707 | 1.880 | Trip | 4.028 |
| 15 | 0.413 | 1.054 | Trip | 5.26 |
| 10 | 0.321 | 0.782 | Trip | 6.55 |
| 5 | 0.241 | 0.533 | Trip | 9.26 |
| 3 | 0.167 | 0.344 | Trip | 9.45 |
| 1 | 0.030 | 0.050 | No Trip | - |

## 2. Effect of different system parameters

The sensitivity of the proposed technique is studied using different system parameters. A power transformer has been installed in two different system configurations. The negative sequence currents are going to be present on both sides of the power transformer with different magnitudes. The magnitude of the negative sequence current on the faulty side is greater than the magnitude of the negative sequence current on the other side. The magnitudes of the negative sequence currents depend on the magnitudes of the negative sequence impedances of circuits on the respective sides of the power transformer. It is known that when the magnitude of the impedance increases then the magnitude of the current will decrease.

The results given in Table 5.3 show the performance of the proposed technique using different system parameters on both sides of the power transformer. It can be seen from Table 5.3 that the proposed technique is going to operate correctly even with different values of system parameters.

Table 5.3 – Results using different system parameter values (Y-Y transformer, turn-to-turn fault applied on the secondary winding)

| *Shorted turns,%* | *Impedance source 1, Ω* | *Impedance source 2, Ω* | $I_{NS\_P}$, *A* | $I_{NS\_S}$, *A* | *Output signal* | |
|---|---|---|---|---|---|---|
| | | | | | *Trip action* | *Trip time, ms* |
| 25 | 1.6 | 17.95 | 0.290 | 2.51 | Trip | 6.24 |
| | 3 | 52.9 | 0.558 | 1.99 | Trip | 4 |
| 15 | 1.6 | 17.95 | 0.177 | 1.365 | Trip | 10.25 |
| | 3 | 52.9 | 0.328 | 1.130 | Trip | 6.25 |
| 10 | 1.6 | 17.95 | 0.146 | 1.007 | Trip | 10.25 |
| | 3 | 52.9 | 0.257 | 0.846 | Trip | 9.25 |
| 5 | 1.6 | 17.95 | 0.131 | 0.728 | Trip | 10.26 |
| | 3 | 52.9 | 0.208 | 0.627 | Trip | 9.25 |
| 3 | 1.6 | 17.95 | 0.125 | 0.631 | Trip | 10.27 |
| | 3 | 52.9 | 0.191 | 0.542 | Trip | 9.24 |
| 1 | 1.6 | 17.95 | 0.125 | 0.541 | Trip | 10.27 |
| | 3 | 52.9 | 0.181 | 0.466 | Trip | 9.26 |

### 5.3.2 Turn-to-turn faults on the primary winding of the power transformer connected in Y-Y

In this study, an internal turn-to-turn fault was applied on the primary winding (LV side) in phase C of the power transformer connected in Y-Y. There is no current transformer saturation. The total number of turns on the primary winding is 150 turns.

The magnitude of the negative sequence current on the primary side ($I_{NS\_P}$) and the magnitude of the negative sequence current on the secondary side ($I_{NS\_S}$) for different percentages of shorted turns on the secondary winding in phase C of the power transformer are shown in Figures 5.38 - 5.42. Since, a turn-to-turn fault is applied on the primary winding, the magnitude of the negative sequence current on the primary side ($I_{NS\_P}$) is greater than the magnitude of the negative sequence current on the secondary side ($I_{NS\_S}$).

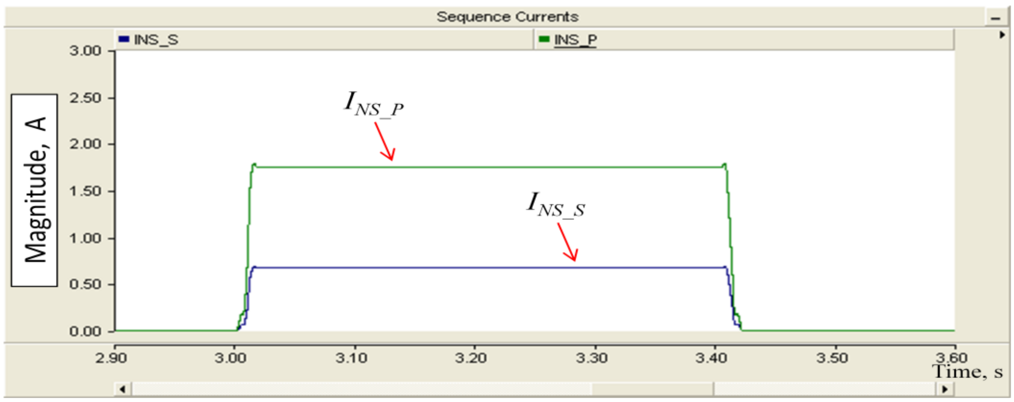



Figure 5.38 – Negative sequence current magnitudes for **25%** shorted turns on primary (Y-Y)

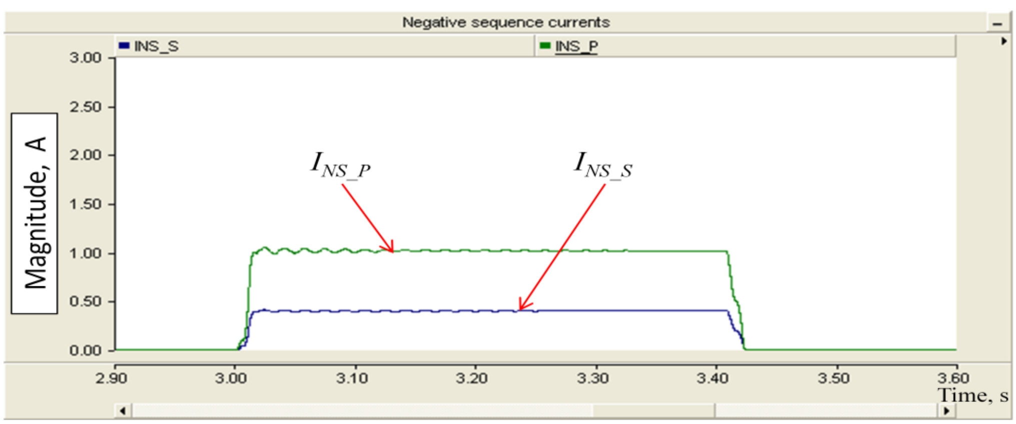



Figure 5.39 – Negative sequence current magnitudes for **15%** shorted turns on primary (Y-Y)

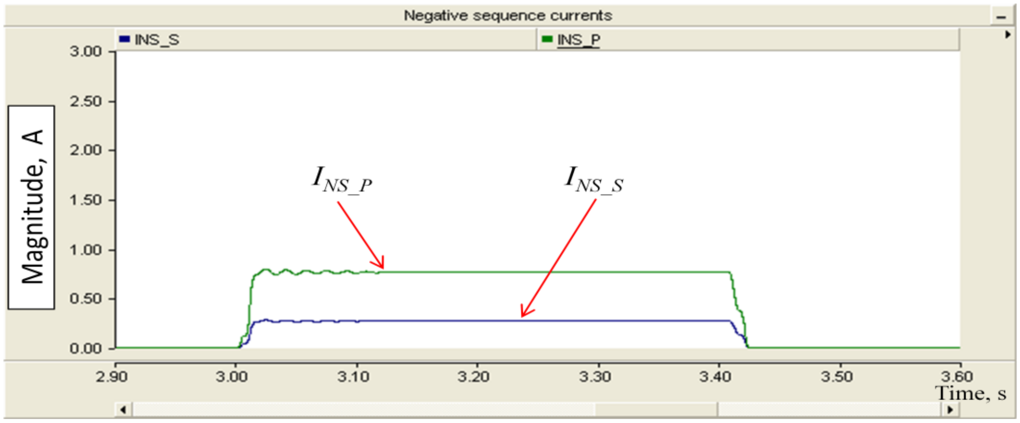



Figure 5.40 – Negative sequence current magnitudes for **10%** shorted turns on primary (Y-Y)

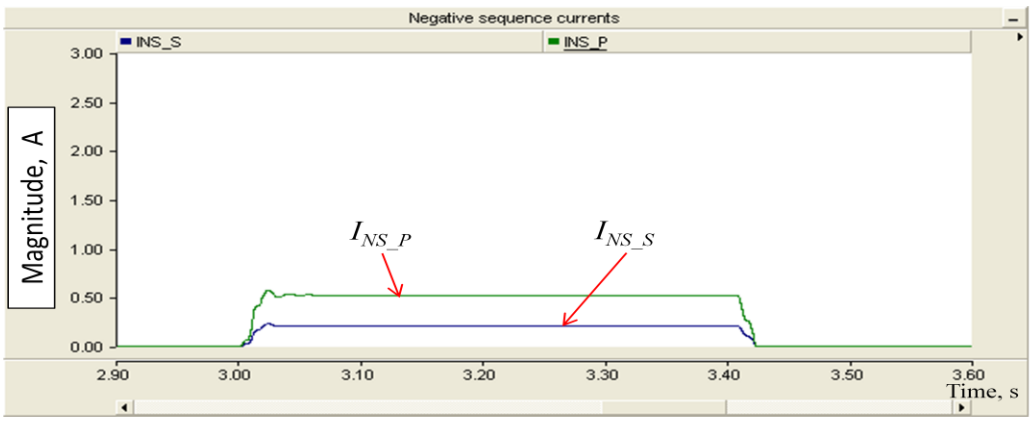



Figure 5.41 – Negative sequence current magnitudes for **3%** shorted turns on primary (Y-Y)

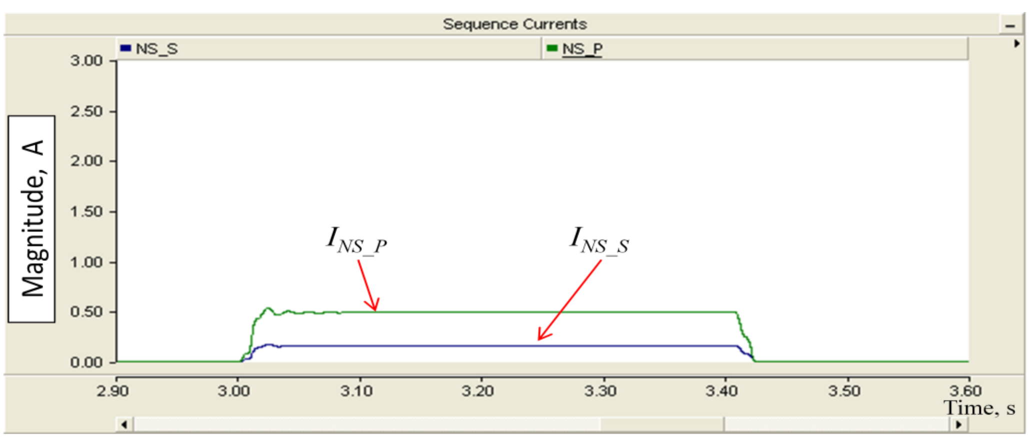



Figure 5.42 – Negative sequence current magnitudes for **1%** shorted turns on primary (Y-Y)

‘Zooming in’ on magnitudes of the two components of the total negative sequence current for different percentages of shorted turns is shown in Figures 5.43 - 5.47.  Magnitudes of negative sequence currents are compared with a preset level which is 1 % (0.05 A) of the differential protection’s base current.

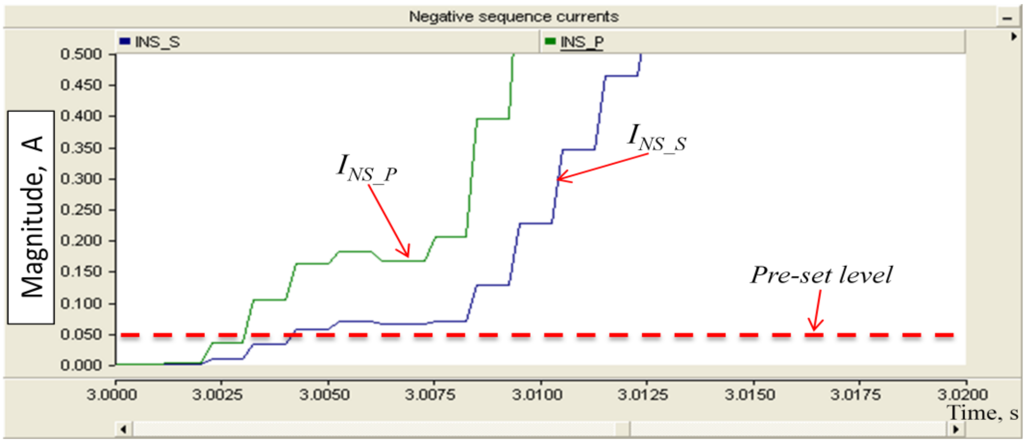



Figure 5.43 – Zooming in on negative sequence current magnitudes for **25%** shorted turns on primary (Y-Y)

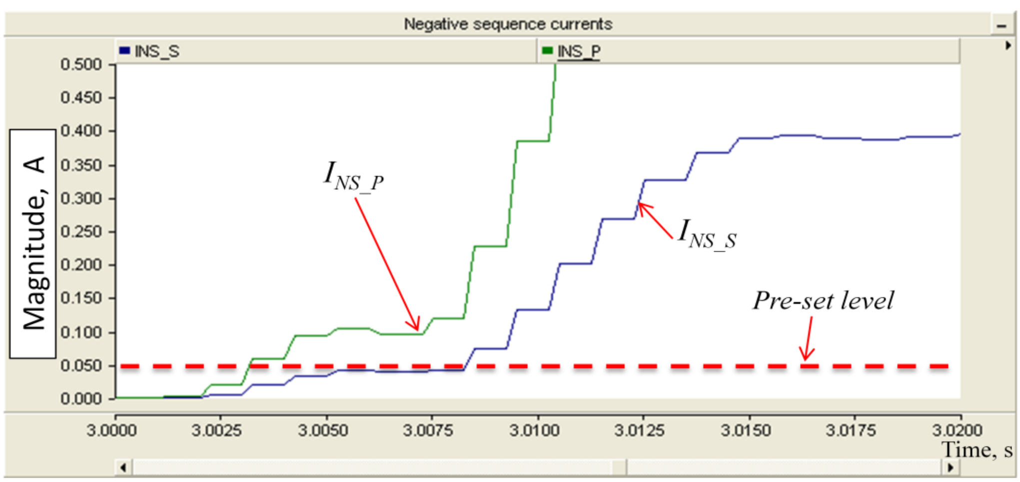



Figure 5.44 – Zooming in on negative sequence current magnitudes for **15%** shorted turns on primary (Y-Y)

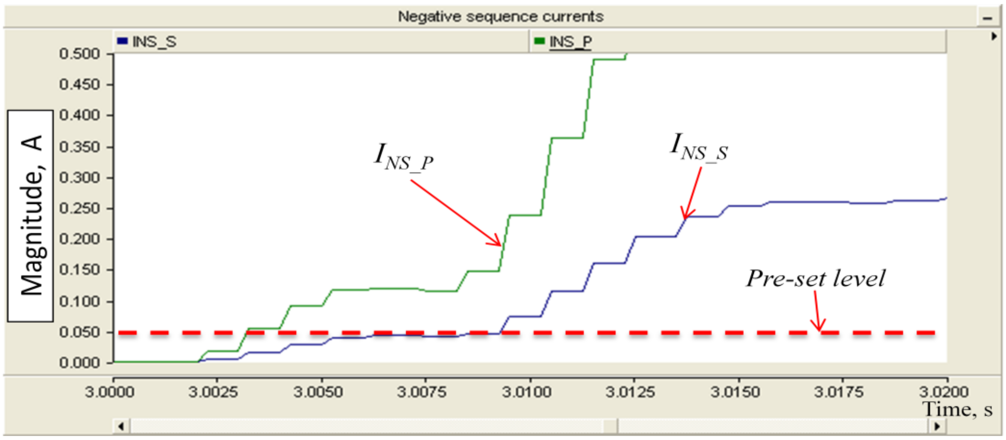



Figure 5.45 – Zooming in on negative sequence current magnitudes for **10%** shorted turns on primary (Y-Y)

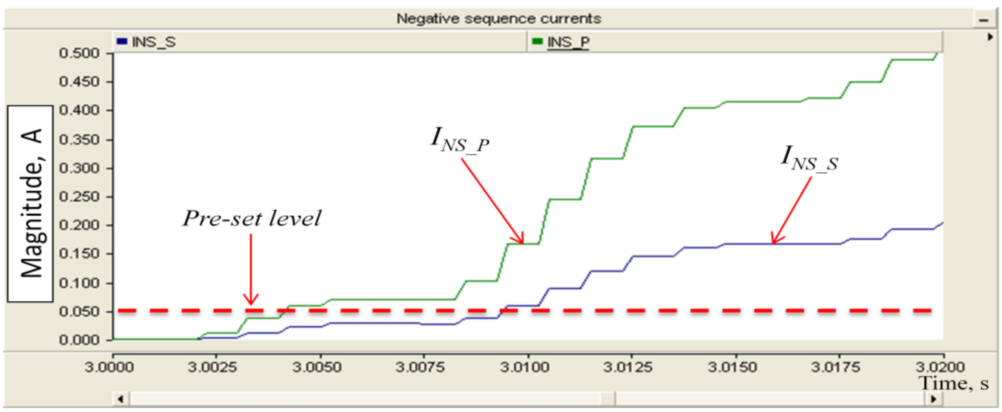



Figure 5.46 – Zooming in on negative sequence current magnitudes for **3%** shorted turns on primary (Y-Y)

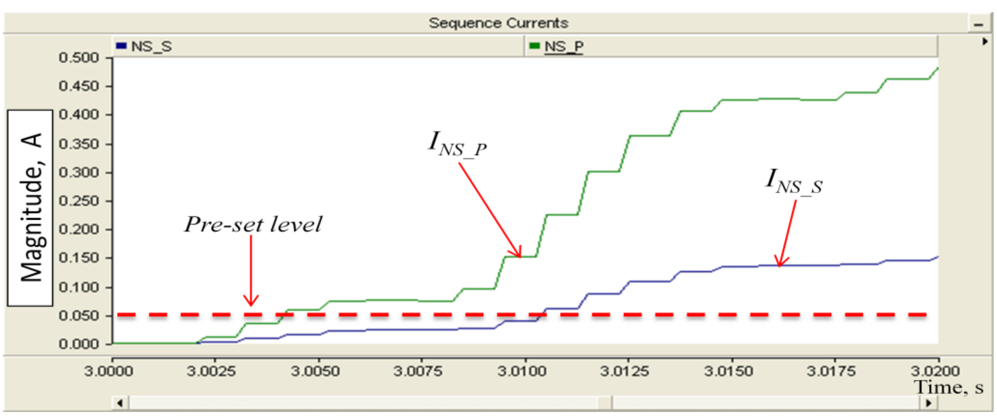



Figure 5.47 – Zooming in on negative sequence current magnitudes for **1%** shorted turns on primary (Y-Y)

Figures 5.48 - 5.52 show the relative phase angle between two phasors of negative sequence currents for various percentages of shorted turns on the primary winding.

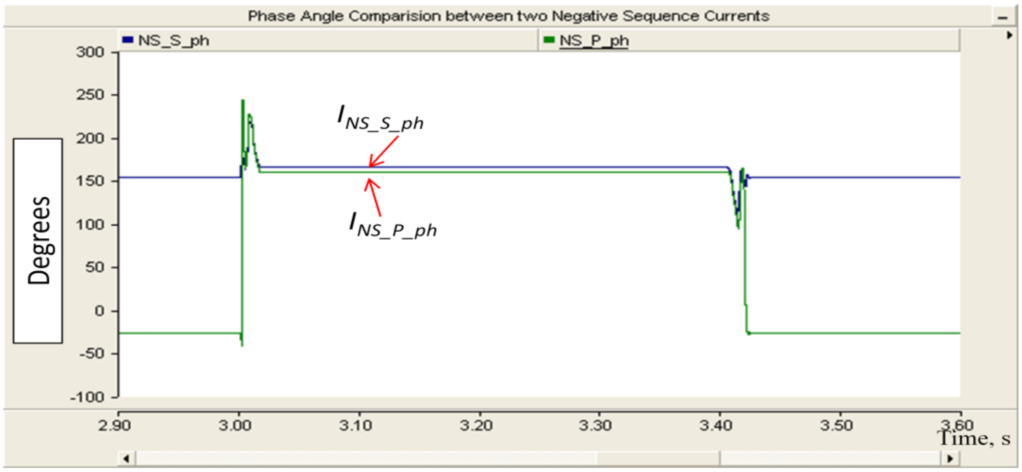



Figure 5.48 – Phase angle comparison between two negative sequence currents for **25%** shorted turns on primary (Y-Y)

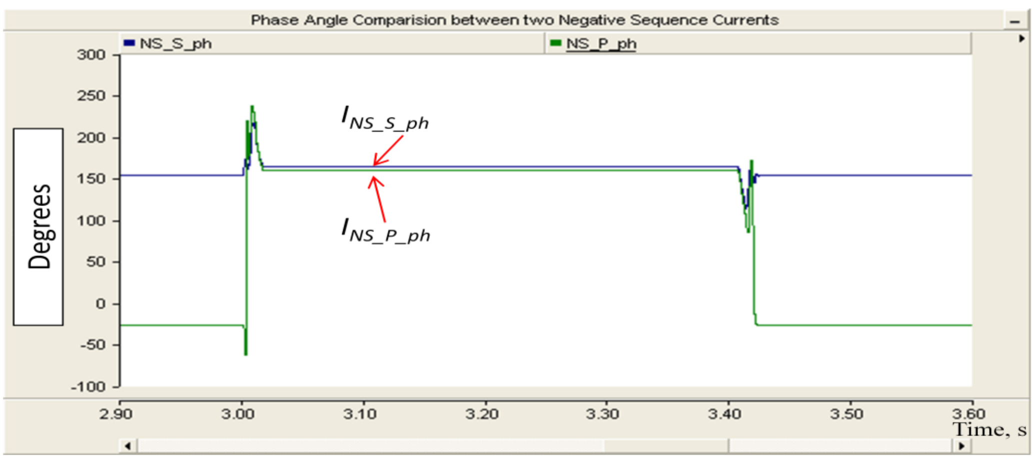



Figure 5.49 – Phase angle comparison between two negative sequence currents for **15%** shorted turns on primary (Y-Y)

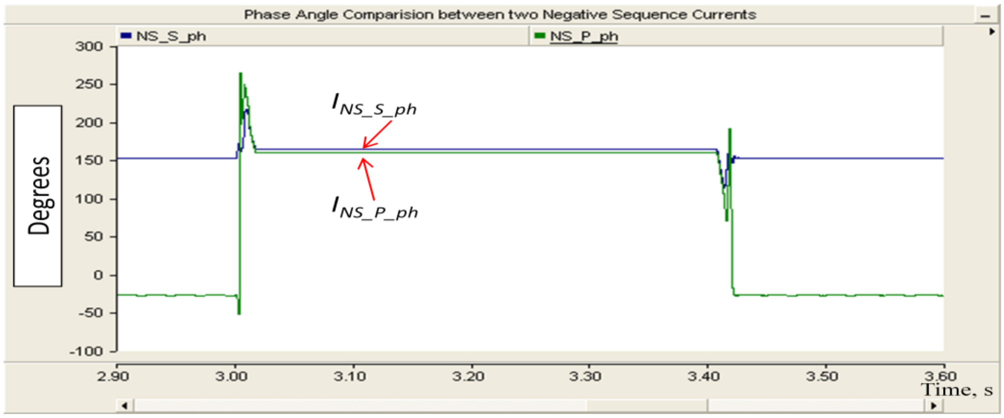



Figure 5.50 – Phase angle comparison between two negative sequence currents for **10%** shorted turns on primary (Y-Y)

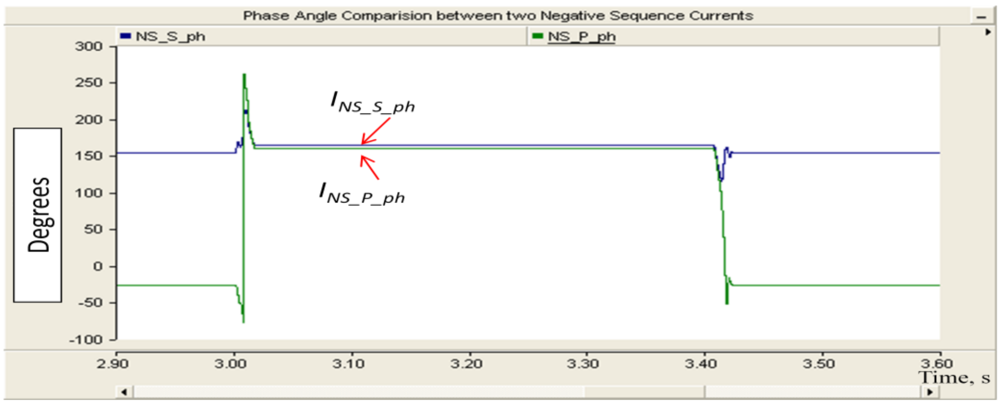



Figure 5.51 – Phase angle comparison between two negative sequence currents for **3%** shorted turns on primary (Y-Y)

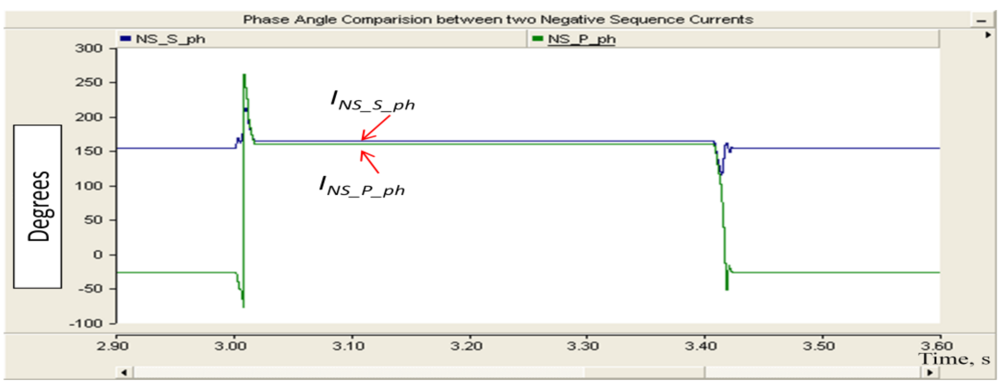



Figure 5.52 – Phase angle comparison between two negative sequence currents for **1%** shorted turns on primary (Y-Y)

As it can be seen from Figures 5.44 - 5.48, the proposed protection technique can detect internal turn-to-turn faults as low as 1% (2 turns) of shorted turns on the primary winding of the power transformer.

### 5.3.2.1 Sensitivity analysis of the proposed relay for turn-to-turn faults on the primary winding (Y-Y)

**1. Effect of the fault resistance**

Table 5.4 gives the measured values of the negative sequence currents on the primary and secondary windings of the power transformer for a bolted turn-to-turn fault on the primary winding with the fault resistance $R_f = 0\Omega$. As it can be seen from Table 5.4, the proposed protection technique detects a bolted turn-to-turn fault on the primary winding for all cases.

Table 5.4 – Turn-to-turn fault on the primary winding of the power transformer connected in Y-Y for various percentages of shored turns($R_f = 0\Omega$)

| *Shorted turns, %* | $I_{NS\_P}$, *A* | $I_{NS\_S}$, *A* | *Output signal* | |
|---|---|---|---|---|
| | | | *Trip action* | *Trip time, ms* |
| 25 | 1.74 | 0.67 | Trip | 4.30 |
| 15 | 1.01 | 0.39 | Trip | 9.2 |
| 10 | 0.76 | 0.268 | Trip | 10.45 |
| 3 | 0.545 | 0.218 | Trip | 10.49 |
| 1 | 0.492 | 0.157 | Trip | 11.77 |

Table 5.5 gives the measured values of the negative sequence currents on the primary and secondary windings of the power transformer for a turn-to-turn fault on the primary winding with the fault resistance of 1 Ohm.

Table 5.5 – Turn-to-turn fault on the primary winding of the power transformer connected in Y-Y for various percentages of shored turns ($R_f = 1\Omega$)

| *Shorted turns, %* | $I_{NS\_P}$, *A* | $I_{NS\_S}$, *A* | *Output signal* | |
|---|---|---|---|---|
| | | | *Trip action* | *Trip time, ms* |
| 25 | 0.92 | 0.35 | Trip | 8.52 |
| 15 | 0.368 | 0.143 | Trip | 10.54 |
| 10 | 0.172 | 0.06 | Trip | 17.76 |
| 3 | 0.01 | 0.0075 | No Trip | - |
| 1 | 0.0031 | 0.00101 | No Trip | - |

As it can be seen from Table 5.5, the sensitivity of the proposed protection technique is reduced.

**2. Effect of different system parameters**

The results given in Table 5.6 show the performance of the proposed technique for detecting a turn-to-turn fault on the primary winding of the power transformer using two sets of different system parameters on both sides of the power transformer. The results presented in Table 5.6 demonstrate the correct operation of the proposed technique even with two different sets of system parameters.

Table 5.6 – Results using different system parameter values (Y-Y transformer, turn-to-turn fault applied on the primary winding)

| *Shorted turns,%* | *Impedance source 1, Ω* | *Impedance source 2, Ω* | $I_{NS\_P}$, *A* | $I_{NS\_S}$, *A* | *Output signal* | |
|---|---|---|---|---|---|---|
| | | | | | *Trip action* | *Trip time, ms* |
| 25 | 1.6 | 17.95 | 0.836 | 0.433 | Trip | 9.46 |
| | 3 | 52.9 | 0.716 | 0.524 | Trip | 8.51 |
| 15 | 1.6 | 17.95 | 0.924 | 0.487 | Trip | 10.51 |
| | 3 | 52.9 | 0.779 | 0.577 | Trip | 4.25 |
| 10 | 1.6 | 17.95 | 0.71 | 0.324 | Trip | 10.53 |
| | 3 | 52.9 | 0.60 | 0.398 | Trip | 5.49 |
| 3 | 1.6 | 17.95 | 0.478 | 0.259 | Trip | 10.75 |
| | 3 | 52.9 | 0.411 | 0.308 | Trip | 9.50 |
| 1 | 1.6 | 17.95 | 0.447 | 0.2085 | Trip | 11.73 |
| | 3 | 52.9 | 0.3689 | 0.271 | Trip | 9.54 |

The performance of the proposed method for the power transformer connected in Δ-Y is given in Appendix B.

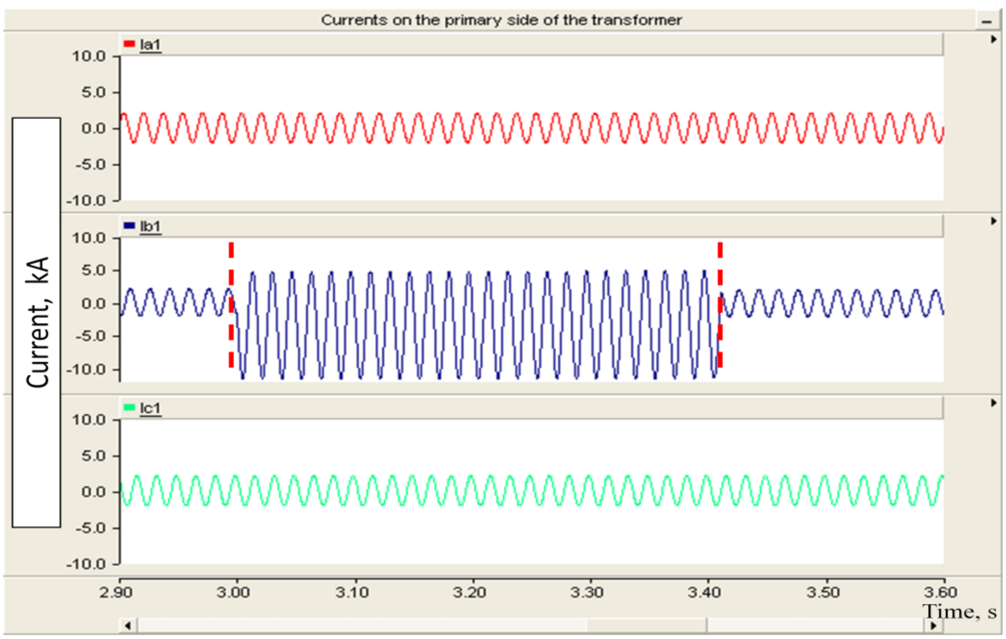
## 5.4 Performance of the proposed method for external faults

The purpose of these studies is to investigate the response of the proposed method based on negative sequence currents to external faults. As it is know from the differential principle, the differential relay should not operate for external faults. The proposed method based was tested for the external phase B-to-ground fault and the external phase B-C fault.

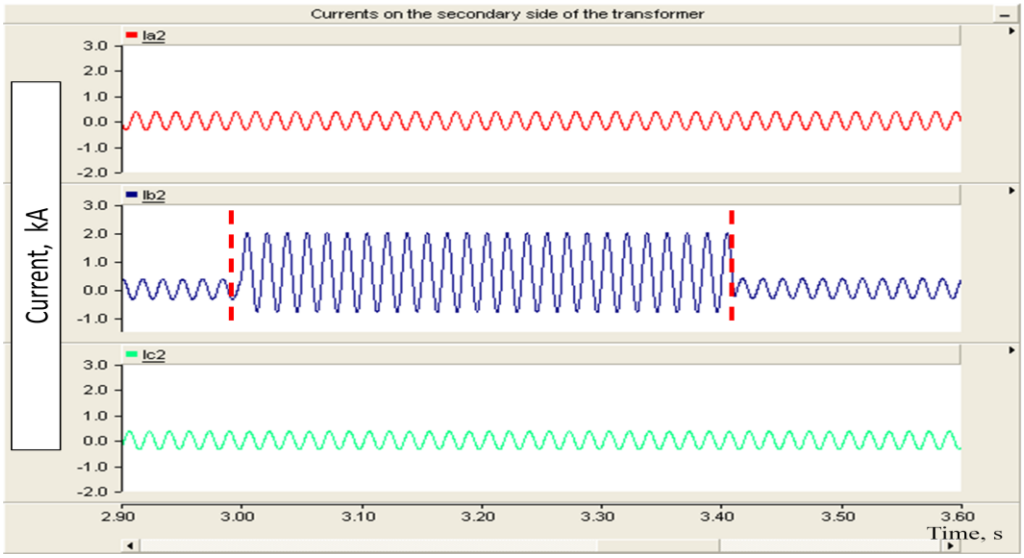
### 5.4.1. External phase B-to-ground fault on the high voltage side of the power transformer

The external phase B-to-ground fault was applied on the secondary (HV) side of the power transformer. The fault is applied at 3 seconds and the duration of the fault is 0.4 seconds.

Figure 5.53 shows phase currents on the primary side ($I_{a1}$, $I_{b1}$, $I_{c1}$) and on the secondary side ($I_{a2}$, $I_{b2}$, $I_{c2}$) of the power transformer during the external phase B-to-ground fault. As it can be seen from Figure 5.53, the changes in the transformer terminal's current in phase B indicate the existence of the fault.




(a) Primary side of the power transformer




(b) Secondary side of the power transformer

Figure 5.53 – Phase currents on both sides of the power transformer for external phase B-to-ground fault on HV side

Figure 5.54 shows magnitudes of the two components of the total negative sequence current.

As it can be seen from Figure 5.54, magnitudes of negative sequence currents were compared with a preset level which is 1% of the differential protection's base current.

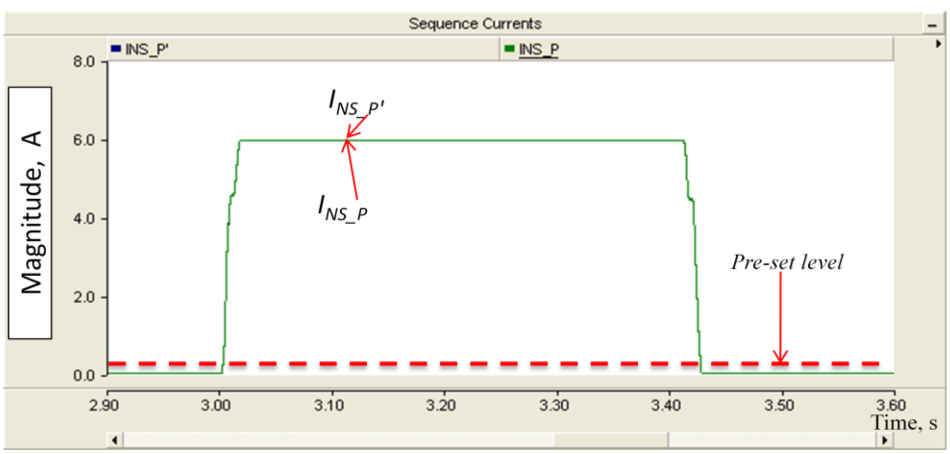



Figure 5.54 – Negative sequence current magnitudes for external phase B-to-ground fault on HV side

Figure 5.55 shows the relative phase angle between two phasors of negative sequence currents which represent the respective contribution during the external phase B-to-ground fault.

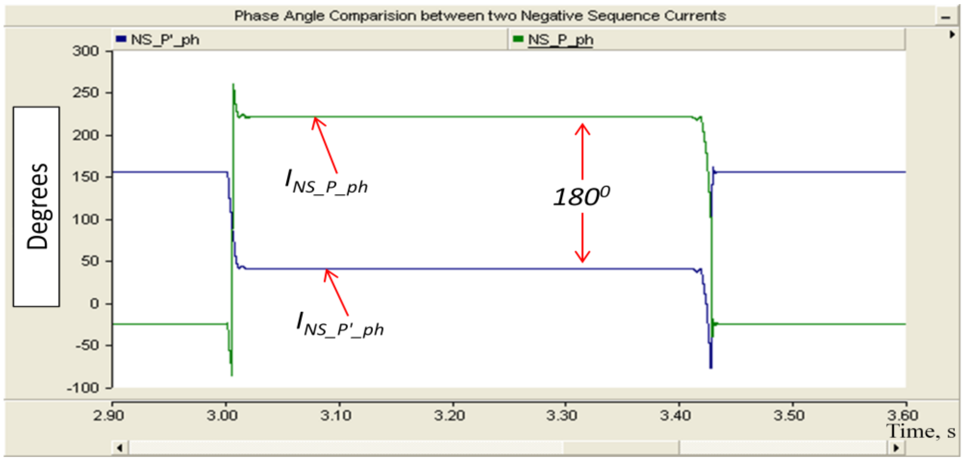



Figure 5.55 – Phase angle between two phasors of negative sequence currents for external phase B-to-ground fault on HV side

Figure 5.56 shows that the proposed technique is going to make a correct decision (i.e. it is not going to trip for the external phase B-to-ground fault).

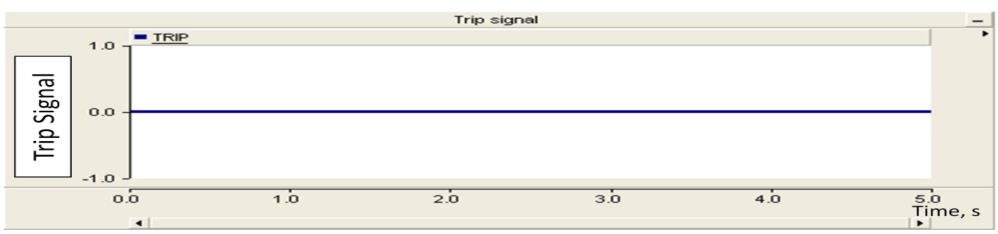
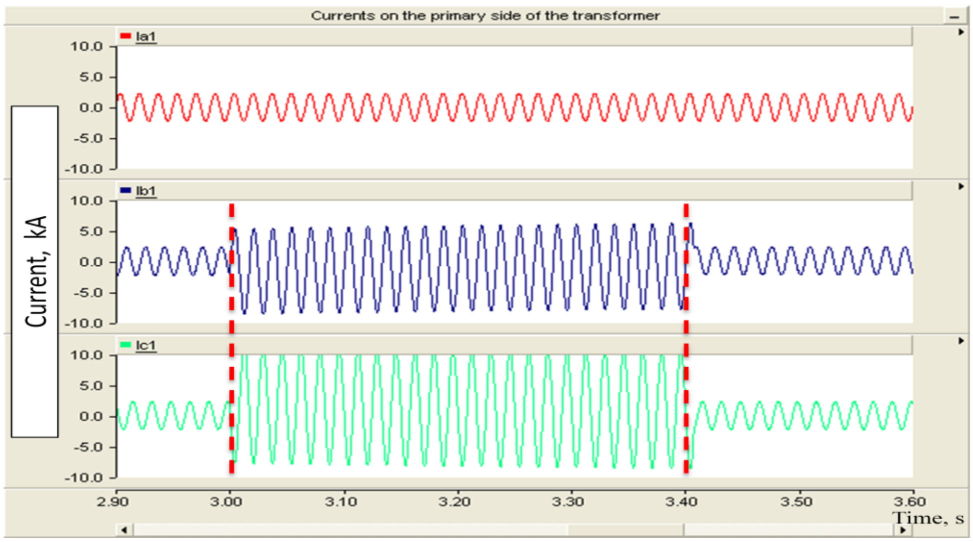


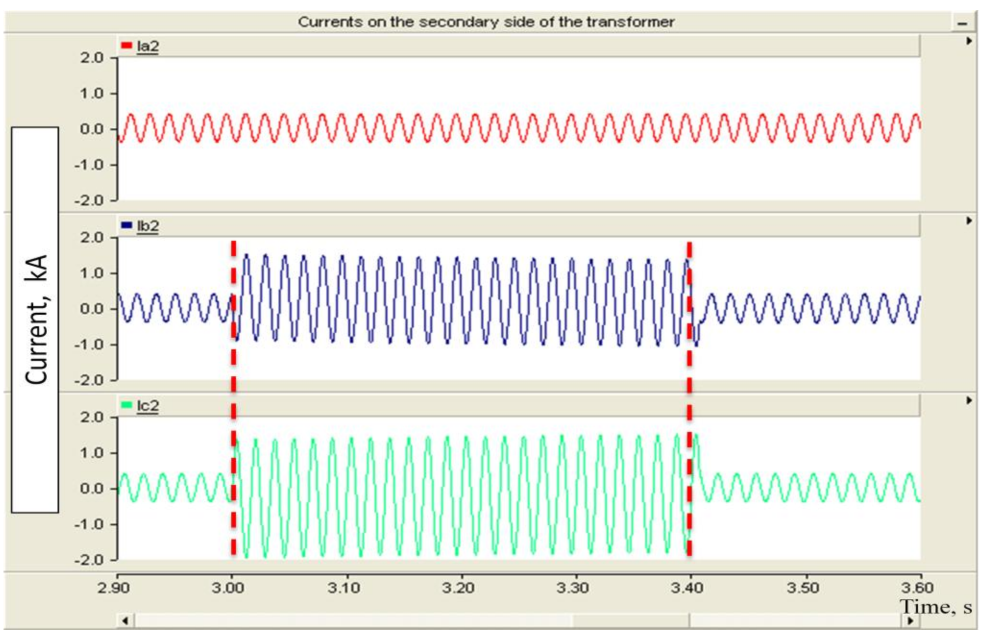

Figure 5.56 – Output signal from the proposed technique for external phase B-to-ground fault on HV side

### 5.4.2 External phase B-C fault on the low voltage side of the power transformer

The results obtained for the external phase B-C fault on the primary (LV) side of the power transformer are shown in Figures 5.57 - 5.60. The time to apply is 3 seconds and the duration of the fault is 0.4 seconds. Figure 5.57 shows phase currents on both sides of the transformer during external phase B-C fault on LV side. As it can be seen from Figure 5.57, the changes in the transformer terminal's current in phase B and C indicate the presence of the fault.




(a) Primary side of the power transformer




(b) Primary side of the power transformer

Figure 5.57 – Phase currents on both sides of the power transformer for external phase B-C fault on LV side

Figure 5.58 shows magnitudes of the two components of the total negative sequence current.

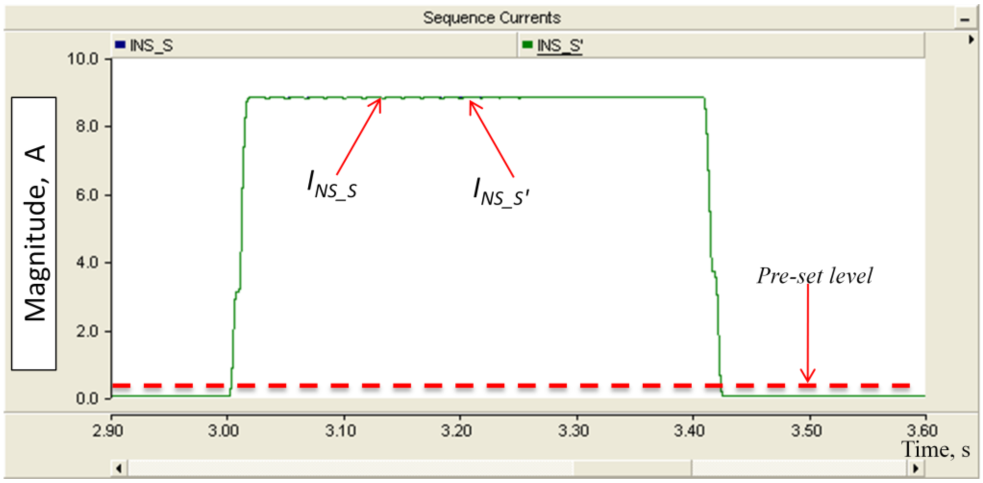



Figure 5.58 – Negative sequence current magnitudes for external phase B-C fault on LV side

Figure 5.59 shows the relative phase angle between two phasors of negative sequence currents which represent the respective contribution during the external phase B-C fault.

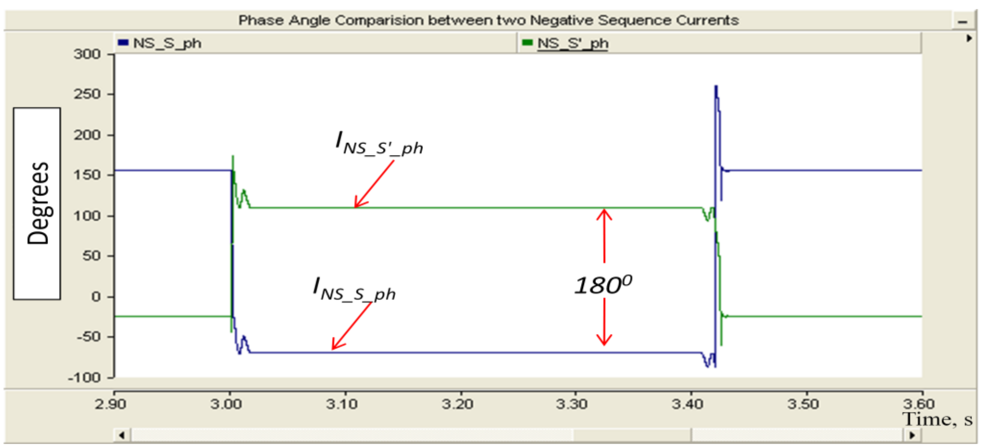



Figure 5.59 – Phase angle between two phasors of negative sequence currents for external phase B-C fault on LV side

Figure 5.60 shows that the proposed technique is again going to operate correctly (i.e. it is not going to trip for the external phase B-C fault).

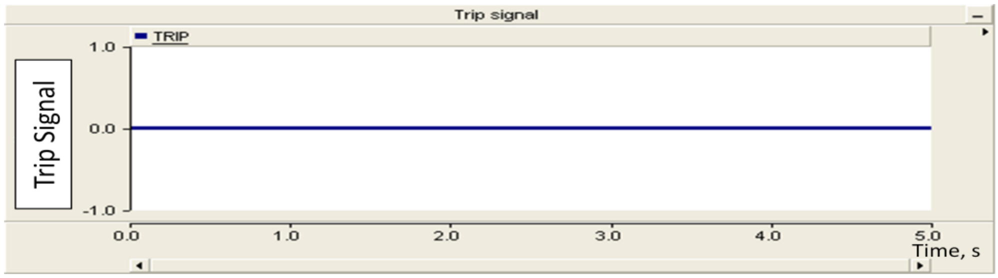



Figure 5.60 – Output signal from the proposed technique for external phase B-C fault on LV side

As it can be seen from Figure 5.54 and Figure 5.58 the negative sequence current enters the healthy transformer on the faulty side and leaves on the other side properly transformed. In other words, the magnitude of the negative sequence current on the faulty side of the transformer equals the magnitude of the negative sequence current on the healthy side of the transformer.

Also, as shown in Figure 5.55 and Figure 5.59, at any point in time after the fault is applied the phase angle between these two phasors equals 180 degrees.

As shown in Figures 5.56 and Figure 5.60 the proposed method based on negative sequence currents shows correct operation for the simulated external faults.

## 5.5 Performance of the proposed method for small unbalances in the power system

Practically, systems rarely have perfectly balanced loads, currents, voltages, or impedances in all three phases. A small unbalance is a common occurrence in a three phase system. When a small unbalance occurs in the three phase system, small negative sequence currents are going to be present. Phase unbalance can be simulated by considering different impedances in the three phases. Table 5.7 gives phase currents due to a small unbalance.

Table 5.7 – Phase currents due to a small unbalance

| *Phase* | *Load Amps* |
|---|---|
| A | 4.1759 |
| B | 4.5976 |
| C | 4.3906 |

According to reference [35] - [36], it is safe for electrical equipment to operate if the maximum line current of one of the three phases does not exceed 10% above the average line current of the three phases.

The average line current is defined as:

$$I_{avg} = \frac{I_{ab} + I_{bc} + I_{ca}}{3}$$

Line current unbalance LCUR (%) ratio is defined as the maximum line current deviation from the average line current magnitude upon the average line current magnitude. For the modelled power system a small line current unbalance ratio equals to 4.78%.

Figure 5.61 shows the negative sequence currents on both sides of the power transformer during the normal operation which are due to the small unbalance in the power system.

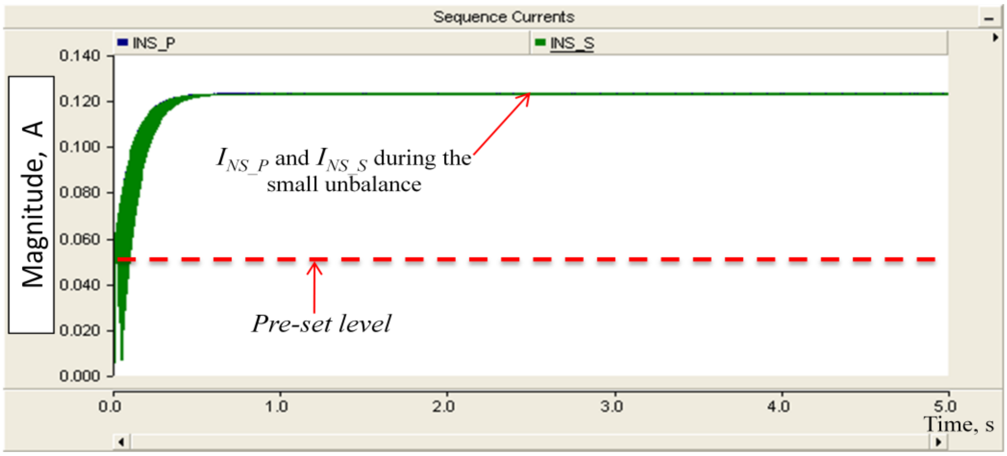



Figure 5.61 – Negative sequence current magnitudes during a small unbalance in the power system

Figure 5.62 shows the relative phase angle between two phasors of the negative sequence currents during a small unbalance in the power system.

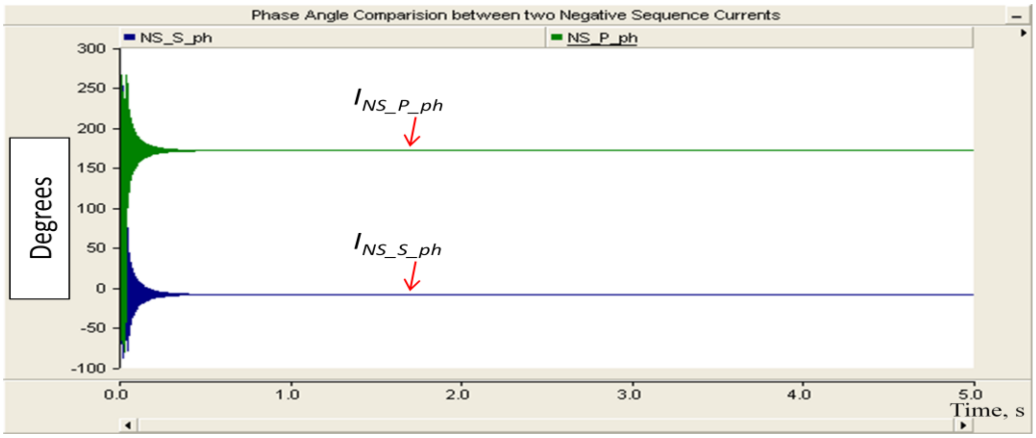



Figure 5.62 – Phase angle between two phasors of negative sequence currents during a small unbalance in the power system

As it can be seen from Figure 5.61, the negative sequence currents during a small unbalance are greater than the minimum pre-set level, but the phase angle between these two phasors equals 180 degrees at any point of time during (Figure 5.62). And for this reason, the proposed technique is going to make a correct decision and is not going to operate for a small unbalance in the power system.

Figure 5.63 shows that the proposed technique trip signal is zero (i.e. it is not going to trip for a small unbalance in the power system).

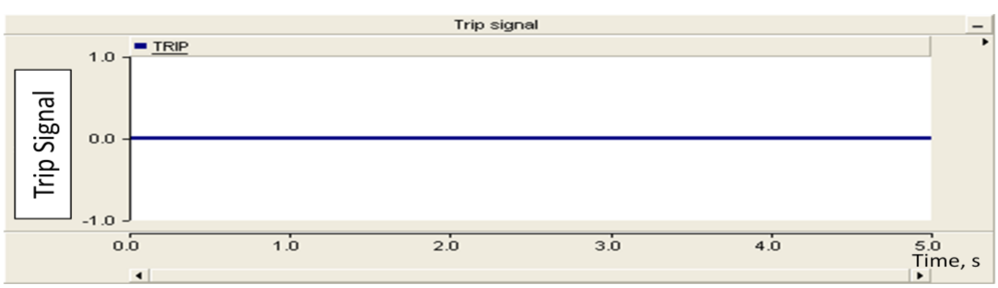



Figure 5.63 – Output signal from the proposed technique for a small unbalance in the power system

The above verifications were important to study the reliability of the technique and showed that the proposed relay is going to be stable for small unbalances in the power system.

## 5.6 Performance of proposed method during the CT saturation

The purpose of this study is to investigate the performance of the proposed method during the CT saturation. As it is known when the current transformer is saturated, it can cause trip delays [37] - [39].

### 5.6.1 CT saturation during turn-to-turn faults

The main focus of this thesis was studying minor internal turn-to-turn faults in power transformers. It is known that current transformers can saturate while carrying fault currents. But during minor internal turn-to-turn faults, the fault current is much less than the fault current during internal unbalanced faults such as phase-to-phase, phase-to-ground, and phase-to-phase-to-ground faults. So for this reason, the CT saturation might not to be a problem during minor turn-to-turn faults (1%, 3%, 5% or 10% turn-to-turn faults).

The CT saturation might affect the performance of negative sequence currents based protection method during other miscellaneous internal faults. The proposed negative sequence current based protection method has significant potential for detecting other types of faults such as phase-to-phase, phase-to-ground, and phase-to-phase-to-ground faults where CT saturation can be a problem. So, one type of internal fault is shown here to study the impact of the CT saturation on the negative sequence logic. Further detailed investigations can be done as part of a future work on the thesis.

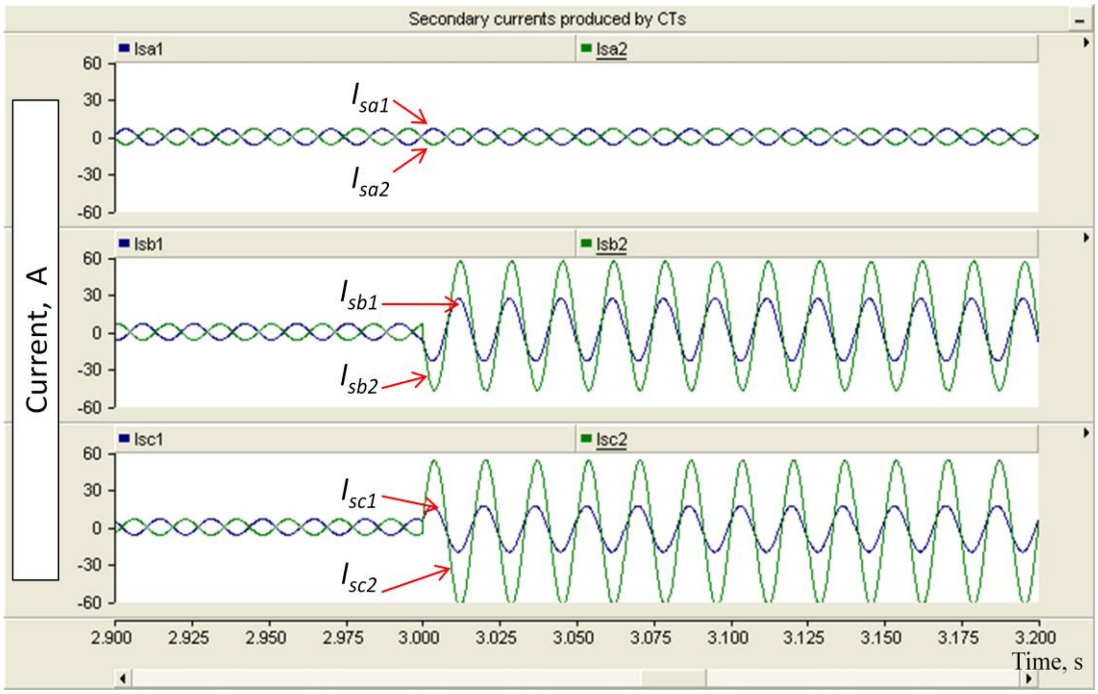
### 5.6.2 CT saturation during other miscellaneous internal faults

The impact of the current transformer saturation on the performance of the proposed method is studied for the internal B-C fault on the secondary side of the power transformer connected in Y-Y.

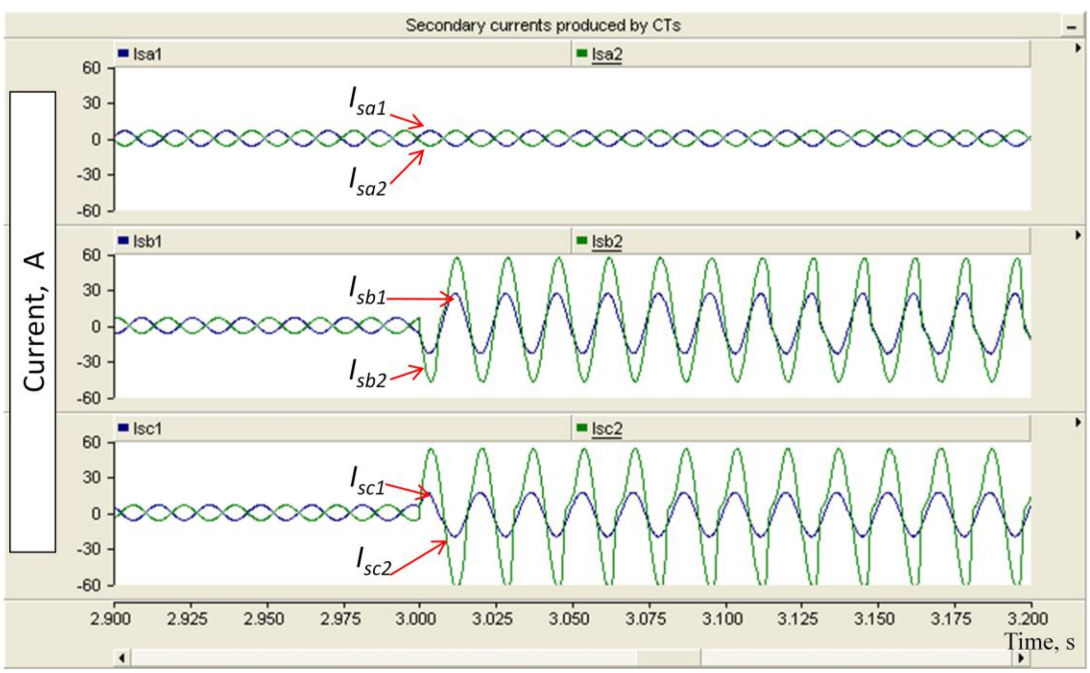
Two current transformers were selected on both sides of the power transformer to model the power system. The current transformer on the primary side of the power transformer has a rating of 1600 to 5 amperes and the current transformer on the secondary side of the power transformer has a rating of 300 to 5 amperes. From the excitation curve, the knee point for the CT on the primary side is over 320 volts and is over 60 volts for the CT on the secondary side of the power transformer. If the secondary voltage of the CT is above the knee point then the CT will saturate. According to the relaying current application guide, the current flowing on the secondary winding of the current transformer is proportional to the voltage in the secondary side of the current transformer and the burden which is connected to the secondary terminal of the current transformer [40]. The burden impedance is typically expressed in values of less than 1Ω. The burden impedance connected to the secondary terminals of each current transformer without saturating their cores is 0.5 Ω. To saturate the power transformer, the burden impedance connected to the secondary terminals of the current transformer has to be larger than the maximum impedance. The burden impedance that was chosen to saturate the current transformers was 7 and 10 Ω.

It is known that if the CT is saturated then the output signal from the current transformer becomes distorted and the actual value of the current is lower than the value calculated by the protective device. This can cause the relay to have a trip delay.

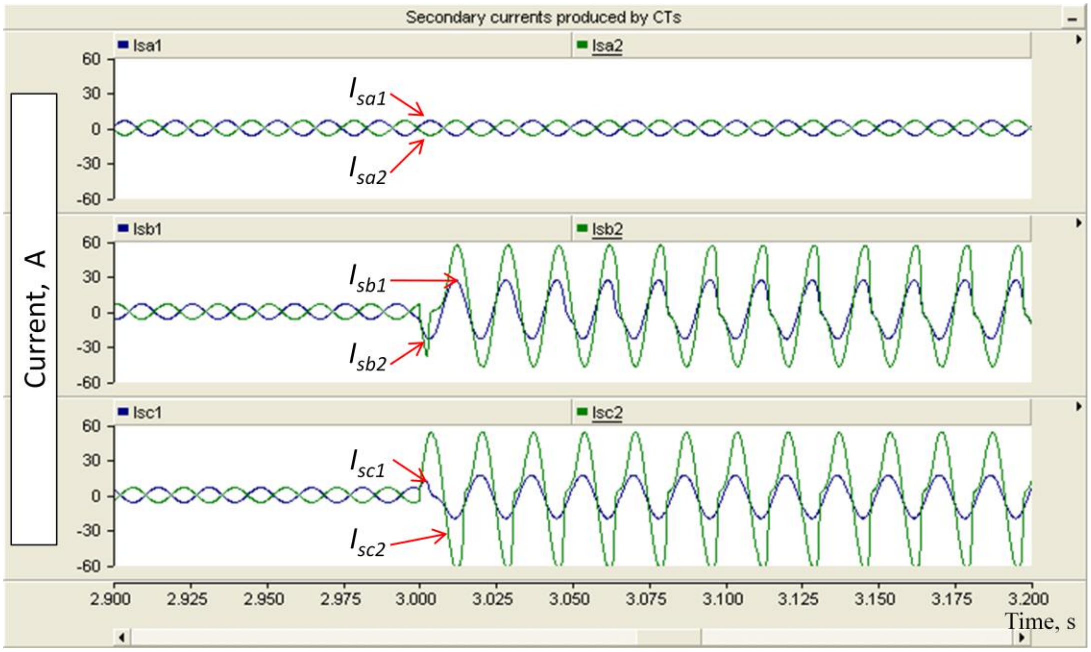
The secondary currents produced by CT's replicate the primary currents in the case of non-saturated CT. When the CT is saturated then the secondary currents have a distorted waveform. Figure 5.64 shows the secondary currents produced by CT on the primary side ($I_{sa1}$, $I_{sb1}$, $I_{sc1}$) and on the secondary side ($I_{sa2}$, $I_{sb2}$, $I_{sc2}$) of the power transformer for non-saturated and saturated CT's.




(a) Non-saturated CT



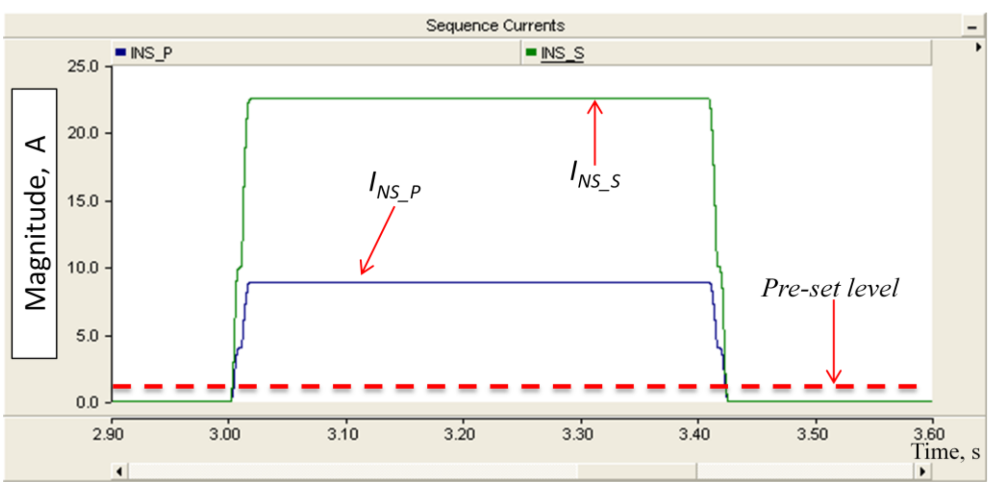

(b) Saturated CT (burden impedance of 7 Ω)



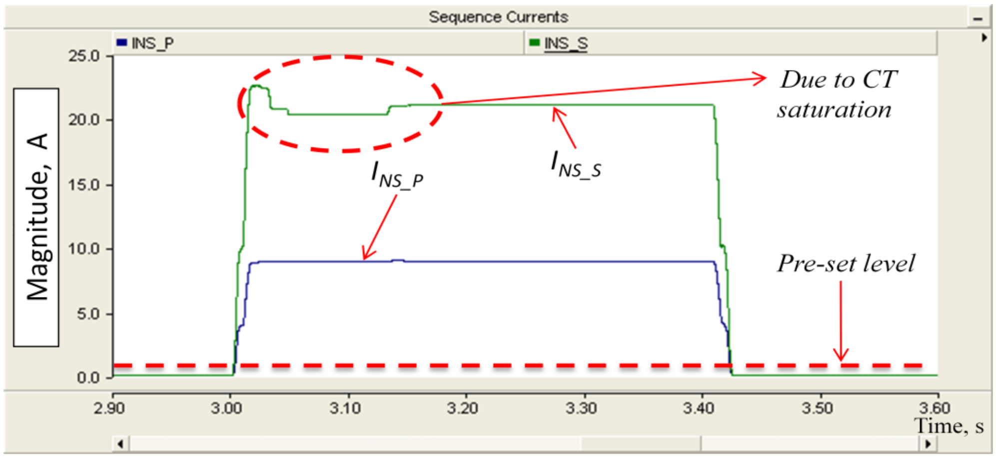

(c) Saturated CT (burden impedance of 10 Ω)

Figure 5.64 – Secondary currents produced by CT for non-saturated and saturated CT cases

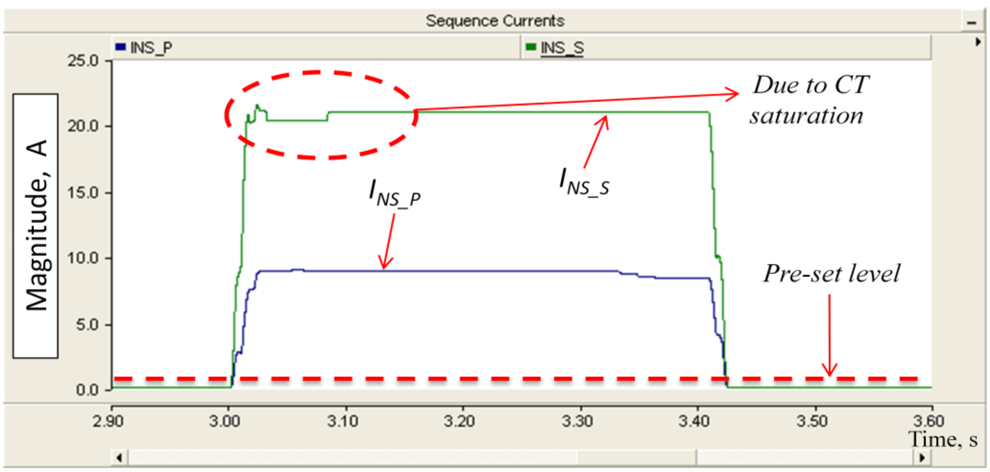
The effect of the CT saturation on the magnitudes of the two components of the total negative sequence current is shown in Figure 5.65.




(a) Non-saturated CT



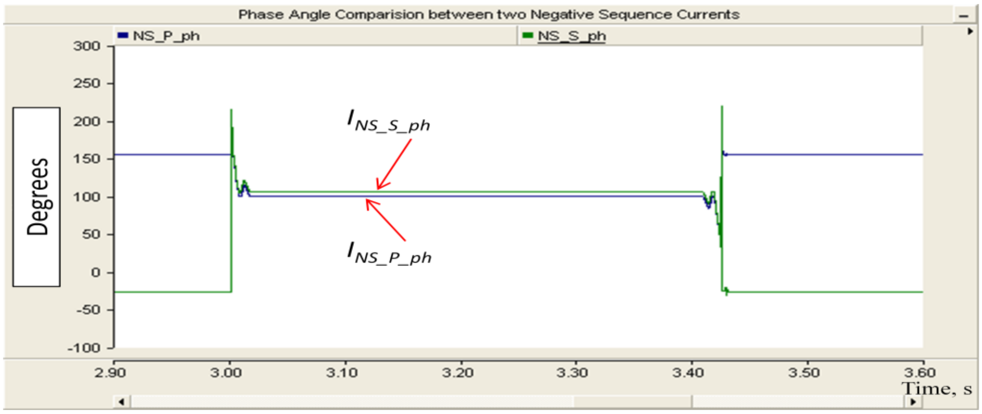

(b) Saturated CT (burden impedance of 7 Ω)



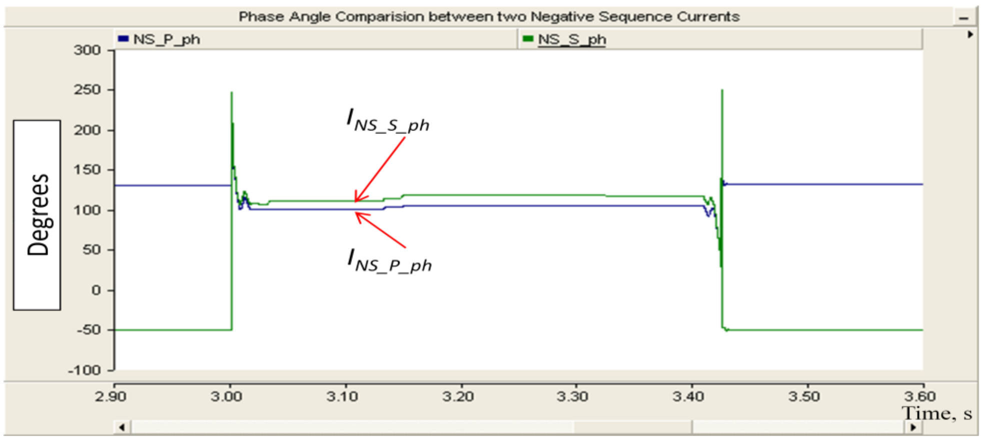

(a) Saturated CT (burden impedance of 10 Ω)

Figure 5.65 – Negative sequence currents magnitudes for internal phase B-C fault for non-saturated and saturated CT cases

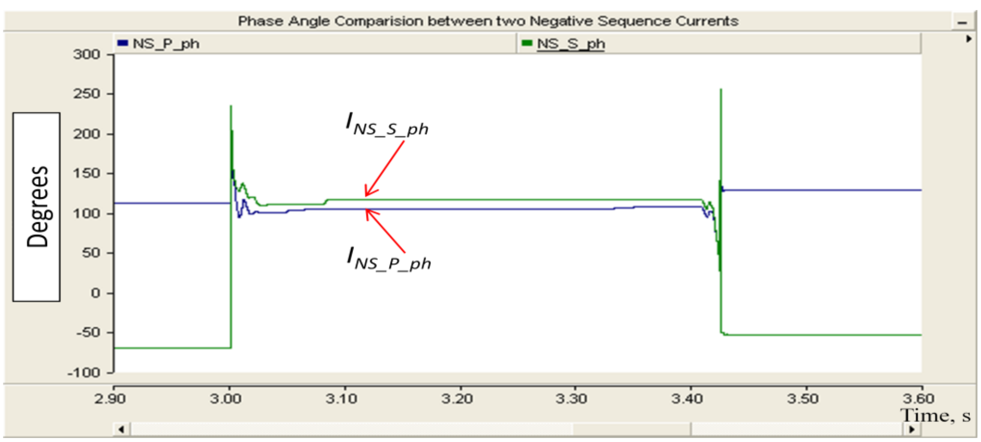
Figure 5.66 shows the relative phase angle between two phasors of negative sequence currents for the cases of non-saturated and saturated CT.




(a) Non-saturated CT




(b) Saturated CT (burden impedance of 7 Ω)

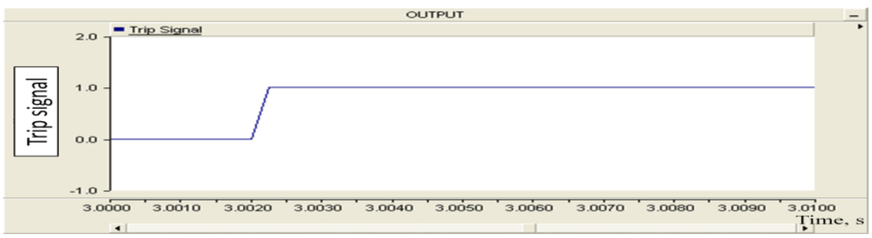



(c) Saturated CT (burden impedance of 10 Ω)

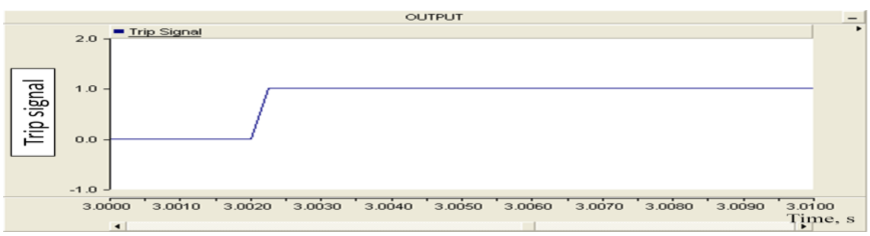
Figure 5.66 – Phase angle between two phasors of negative sequence currents for phase B-C fault for non-saturated and saturated CT cases

As it can be seen from Figure 5.66, the CT saturation causes the measured relative phase angle between two phasors of negative sequence currents to be slightly different compared to the non-saturated case. This is a factor that needs to be taken into account while determining the tolerable phase shift between the two phasors. For the non-saturated case, the phase shift is 3 degrees whereas for the saturated case with burden impedance of 7 Ohm, the phase shift is 12 degrees and for the saturated case with burden impedance of 10 Ohm, the phase shift is 23 degrees.

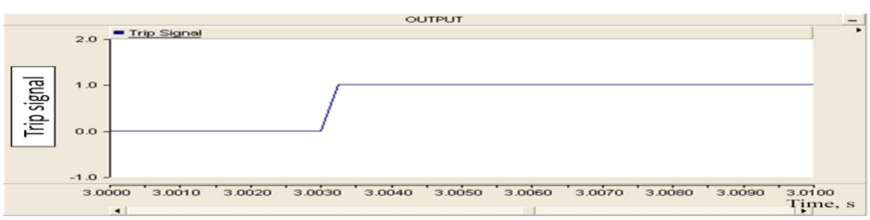
Figure 5.67 shows the output signal from the technique based on negative sequence currents for phase A-B fault for the cases of non-saturated and saturated CT.




(a) Non-saturated CT




(b) Saturated CT (burden impedance of 7 Ω)




(c) Saturated CT (burden impedance of 10 Ω)

Figure 5.67 – Output signal from the proposed technique for phase B-C fault for non-saturated and saturated CT cases

As it can be seen from Figure 5.67, the CT saturation is going to result in trip delays similar to the traditional differential relays.

## 5.7 Performance of the proposed method during inrush current

As it is known, the inrush current is caused by energizing the power transformer. Normally, the magnitude of the energization current is about 1-2% of the rated current under steady state operating conditions. When the power transformer is energized, the magnitude of the energization current can become ten times higher than the full-rated current. This transient process causes the traditional differential relay to trip.

The purpose of this study is to investigate the effect of the inrush current on the performance of negative sequence currents based protection method. To see the performance of the proposed technique during the inrush current, the inrush current phenomenon was recreated. An inrush current can occur when sudden energization of the power transformer happens. The sudden energization of the power transformer can happen when circuit breakers on both sides of the power transformer are opened for a short period of time and then closed causing the energization of the power transformer. Circuit breakers on both sides of the power transformer were opened at 2.0 sec. and were closed at 2.05sec. Figure 5.68 shows magnitudes of the two components of the total negative sequence current when the inrush current is present.

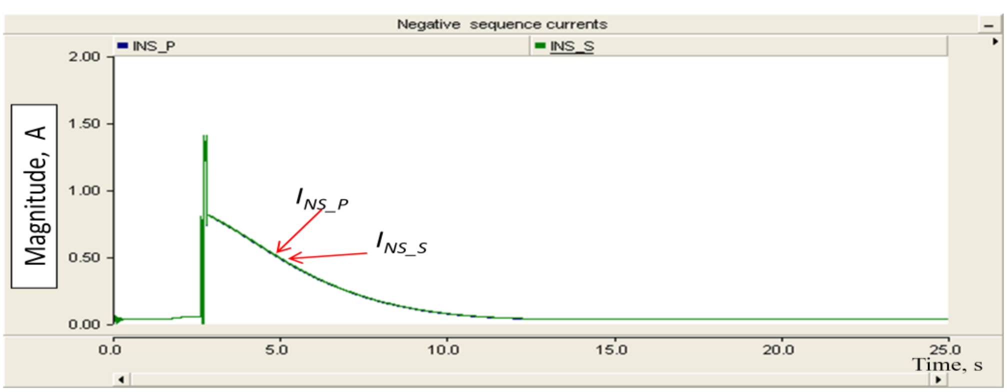



Figure 5.68 – Negative sequence currents magnitudes during inrush current phenomenon

Figure 5.69 shows the relative phase angle between two phasors of negative sequence currents, which represent the respective contribution when the inrush current is present.

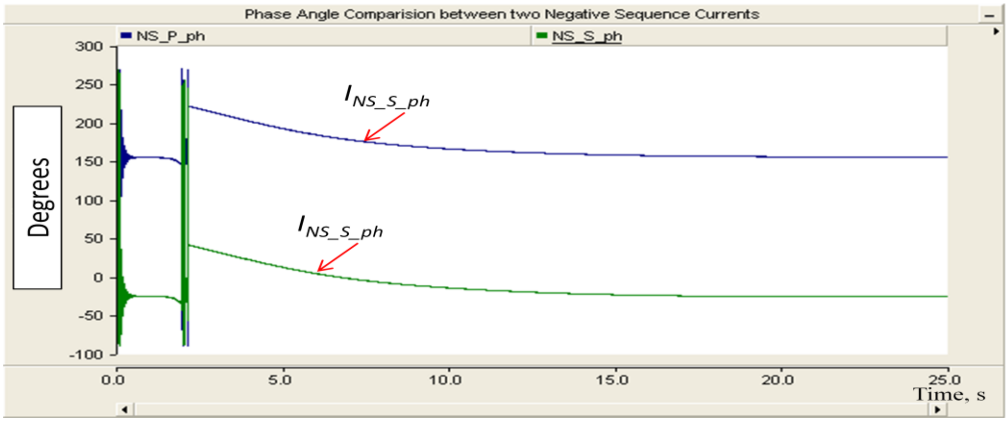



Figure 5.69 – Phase angle between two phasors of negative sequence currents during inrush current phenomenon

As it can be seen from Figure 5.69, the phase angle between these two phasors equals 180 degrees during the inrush current. And for this reason, the proposed technique is going to operate correctly (i.e. it is not going to operate during the inrush current phenomenon).

Figure 5.70 shows that the proposed technique is not going to trip for during the inrush current.

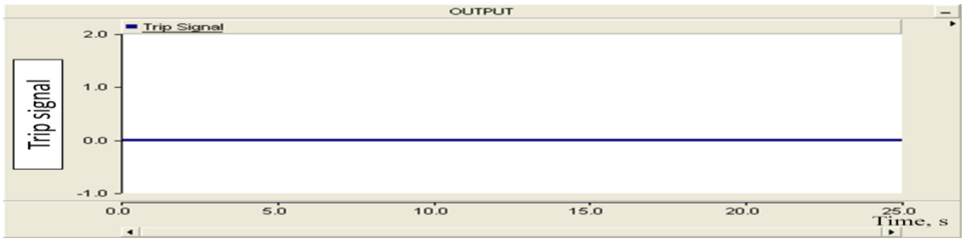



Figure 5.70 – Output signal from the proposed technique during the inrush current

## 5.8 Summary

Performance studies using the traditional differential protection method and the proposed method are presented in this chapter. Firstly, the traditional differential protection is used to investigate how accurately internal turn-to-turn faults can be detected. Also, the sensitivity of the traditional differential protection is shown in this chapter. Secondly, the effectiveness of the negative sequence currents based protection method was demonstrated. The performance of the proposed method was investigated for various cases including different numbers of shorted turns of the transformer, different value of the fault resistances, different values of the system parameters, different connections of the power transformer, during the CT saturation and the inrush current. The proposed method was also tested during small imbalances in the power system and for different external faults of the power transformer.

Simulation results indicate that:

1. The traditional differential protection lacks sensitivity to detect minor internal turn-to-turn faults which involve less than 10% of turns. The traditional differential protection method is not sensitive to minor internal turn-to-turn faults because the changes in the transformer terminal's current are quite small and the ratio of transformation between the whole winding and the short-circuited turns is quite small.

2. The proposed method is very sensitive in detecting minor internal turn-to-turn faults and can detect turn-to-turn faults even when 1% of turns are shorted.

3. The proposed method shows the correct operation for different system parameters and different connections of the power transformer.

4. The proposed method can correctly distinguish between external faults, small imbalances in the power system and internal faults.

5. The performance of the proposed method reveals that this relay can operate correctly if current transformers are saturated.

   The results show that the proposed method can provide a fast and sensitive approach for identifying minor internal turn-to-turn faults in power transformers. Performance analysis shows that this relay has advantages over the traditional differential relay.

# 6. SUMMARY AND CONCLUSIONS

## 6.1 Summary

The power transformers can sometimes fail due to different factors. Common among many of the power transformer failure modes is a shorted turn. It is very important to identify minor internal turn-to-turn faults before they develop into more serious and costly to repair faults. In order to detect these types of faults, a highly sensitive and fast method is required. This thesis described a new negative sequence current based protection method which was capable of detecting minor internal turn-to-turn faults (even faults involving 1% of turns).

The problem associated with detecting minor internal turn-to-turn faults within the power transformer such as low sensitivity of the existed protection methods was described in Chapter 1. The previous methods such as methods based on electromagnetic equations of a transformer, on increments of the flux linkage, on transient detection using DWT, on combination of DWT and ANN for detecting internal turn-to-turn faults were discussed as well. Chapter 2 provided a detailed description about symmetrical components and sequence networks for various types of faults and the transformer's internal turn-to-turn faults. Chapter 3 gave a detailed description about the new protection method based on negative sequence currents. Negative Sequence currents exist during unsymmetrical faults long enough for the relay to make the proper decision. The advantage of using negative sequence currents compared to zero sequence currents is that they can provide coverage for phase-to-phase and turn-to-turn faults as well as for ground faults. Chapter 4 gave the complete description of the modeled power system, the traditional differential protection model and the detailed description of the model of negative sequence currents based protection method. The performance of the traditional differential protection and the proposed protection method for various case studies was presented in Chapter 5. It was shown that the traditional differential protection lacks sensitivity whereas the proposed method is very sensitive to minor internal turn-to-turn faults. The performance of the proposed technique was verified using different numbers of shorted turns of the transformer, different values of the fault resistances, different values of the system parameters, different connections of the power transformer, during the CT saturation, and the inrush current.

## 6.2 Conclusion

This research work demonstrated that it is possible to develop a customized application for detecting internal turn-to-turn faults using negative sequence currents. The performance of the traditional differential protection was studied for different percentages of shorted turns. It was found that the traditional differential protection lacks sensitivity to detect winding faults which involve less than 10% of turns. The proposed protection scheme was evaluated with different cases, which included different numbers of shorted turns of the transformer, different values of the fault resistances, different values of the system parameters, different connections of the power transformer, during the CT saturation, and the inrush current. The results illustrated that the proposed method is able to detect minor internal turn-to-turn faults which involve only 2 turns (1% of turns) and a trip signal was activated within 1 cycle. The proposed method discriminated accurately between external and internal faults. In addition, the proposed method operated correctly under different system parameters, different connections of the power transformer, during the CT saturation, and the inrush current.

## 6.3 Contribution

Specifically the thesis made the contributions which are described in the next paragraph.

A power transformer model for simulating internal turn-to-turn faults was developed using PSCAD/EMTDC. The change in impedance of the total phase is difficult to calculate when the fault involves few shorted turns. The values of the leakage reactance are not available in the literature and are very difficult to find. Using Finite Element Analysis, the leakage reactance of the power transformer for various percentages of shorted turns on the primary and secondary windings was obtained.

The previous literature stated that the negative sequence current based method is not going to be more sensitive than the phase current differential protection [25]. It also has been claimed that the negative sequence current scheme is suited for careful customized application. However, it was shown via an extensive simulation studies in the thesis that the negative sequence current scheme is going to be much more sensitive than the traditional differential protection and can detect even when 1% of turns are shorted. Also, the proposed scheme did not require any extra customization more than the traditional differential protection scheme.

## 6.4 Future work

Results presented in this thesis showed that the proposed protection method which has higher sensitivity for winding turn-to-turn faults may be implemented as an additional logic on top of the traditional differential protection. In order to protect power transformers with the new differential protection method and replace the traditional differential protection, the performance of the proposed method has to be investigated under all factors which affect the traditional differential protection. As future work:

- The performance of the proposed method can to be tested for transformer on-load tap-changing operation and over excitation conditions.
- The simulation results obtained from PSCAD/EMTDC simulation package can be validated using the Real Time Digital Simulator (RTDS$^{TM}$) which will allow the closed-loop testing of protection similar to an actual system. This will help in strengthening the research findings.

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# APPENDIX A

# DATA AND PARAMETERS OF THE MODELLED POWER SYSTEM

Table A.1 – Parameters of source 1

| *Base MVA* | *Voltage, kV* | *Phase angle, degrees* | *Internal Impedance, Ω* | *Impedance phase angle, degrees* | *Frequency, Hz* |
|---|---|---|---|---|---|
| 100 | 39.83 | 0 | 1.6 | 80 | 60 |

Table A.2 – Parameters of source 2

| *Base MVA* | *Voltage, kV* | *Phase angle, degrees* | *Internal Impedance, Ω* | *Impedance phase angle, degrees* | *Frequency, Hz* |
|---|---|---|---|---|---|
| 100 | 229.99 | 20 | 52.9 | 80 | 60 |

Table A.3 – Parameters of CT on primary side

| *Primary turns* | *Secondary turns* | *Secondary resistance, Ohm* | *Secondary inductance, H* | *Frequency, Hz* |
|---|---|---|---|---|
| 1 | 320 | 0.5 | 0.8e-3 | 60 |

Table A.4 – Parameters of CT on secondary side

| *Primary turns* | *Secondary turns* | *Secondary resistance, Ohm* | *Secondary inductance, H* | *Frequency, Hz* |
|---|---|---|---|---|
| 1 | 60 | 0.5 | 0.8e-3 | 60 |

Table A.5 – Parameters of a single phase power transformer

| *Base MVA* | *Primary voltage, kV* | *Secondary voltage, kV* | *System frequency, Hz* | *Turns on LV side* | *Turns on HV side* | *Magnetizing current, %* |
|---|---|---|---|---|---|---|
| 33.3 | 23 | 132.79 | 60 | 150 | 866 | 0.1 |

Table A.6 – Leakage reactance of a single phase transformer for internal turn-to-turn fault on the secondary winding of the power transformer

| | *Leakage reactance,%* | | | | | |
|---|---|---|---|---|---|---|
| | *25% turns shorted* | *15% turns shorted* | *10% turns shorted* | *5% turns shorted* | *3% turns shorted* | *1% turns shorted* |
| *LV-HV* | 15.08 | 15.08 | 15.08 | 15.08 | 15.08 | 15.08 |
| $LV - HV_{top}$ | 121.82 | 156.87 | 178.49 | 204.85 | 218.7 | 232.6 |
| $LV - HV_{shorted}$ | 66.4 | 109.88 | 141.92 | 184.82 | 207.73 | 230.64 |
| $LV - HV_{bottom}$ | 62.74 | 32.97 | 23.71 | 17.68 | 14.82 | 0.1196 |
| $HV_{top} - HV_{shorted}$ | 131.9 | 106.58 | 92.09 | 71.13 | 65.15 | 59 |
| $HV_{top} - HV_{bottom}$ | 278.49 | 252.92 | 243.46 | 236.47 | 234.505 | 232.54 |
| $HV_{shorted} - HV_{bottom}$ | 162.34 | 181.61 | 194.02 | 210.83 | 221.195 | 231.56 |

Table A.7 – Leakage reactance of a single phase transformer for internal turn-to-turn fault on the primary winding of the power transformer

| | *Leakage reactance,%* | | | | |
|---|---|---|---|---|---|
| | *25% turns shorted* | *15% turns shorted* | *10% turns shorted* | *3% turns shorted* | *1% turns shorted* |
| *HV-LV* | 15.08 | 15.08 | 15.08 | 15.08 | 15.08 |
| $LV_{top}$ - $HV$ | 128.48 | 164.42 | 200.36 | 219.09 | 247.69 |
| $LV_{shorted}$ - $HV$ | 69.55 | 113.14 | 156.73 | 204.40 | 234.097 |
| $LV_{bottom}$ - $HV$ | 71.38 | 36.97 | 25.6 | 16.87 | 7 |
| $LV_{top}$ - $LV_{shorted}$ | 147.45 | 113.11 | 78.77 | 46.88 | 22.352 |
| $LV_{top}$ - $LV_{bottom}$ | 308.20 | 277.56 | 246.92 | 244.63 | 217.512 |
| $LV_{shorted}$ - $LV_{bottom}$ | 178.16 | 196.40 | 214.64 | 222.14 | 237.056 |

# APPENDIX B

# PERFORMANCE OF THE PROPOSED METHOD FOR Δ-Y TRANSFORMER

In this study, the internal turn-to-turn fault occurred on the secondary winding (HV side) in phase C of the power transformer connected in Δ-Y.

Figures B.1 - B.3 show the magnitude of the negative sequence current on the primary side ($I_{NS\_P}$) and the magnitude of the negative sequence current on the secondary side ($I_{NS\_S}$) for 5%, 3%, and 1% of shorted turns. Both magnitudes are compared with a preset level which is 1 % (0.05 A) of the differential protection's base current.

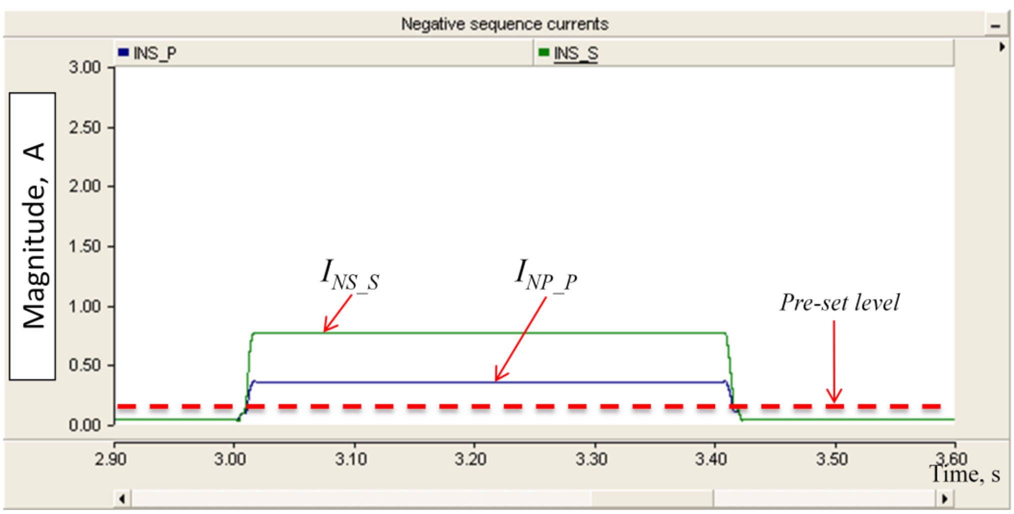


Figure B.1 – Negative sequence current magnitudes for **5%** shorted turns on secondary (Δ-Y)

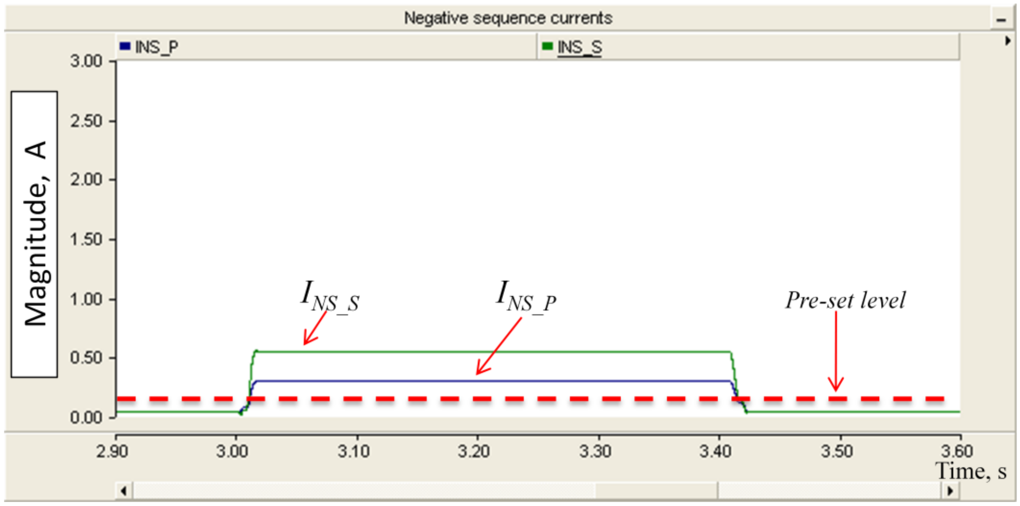


Figure B.2 – Negative sequence current magnitudes for **3%** shorted turns on secondary (Δ-Y)

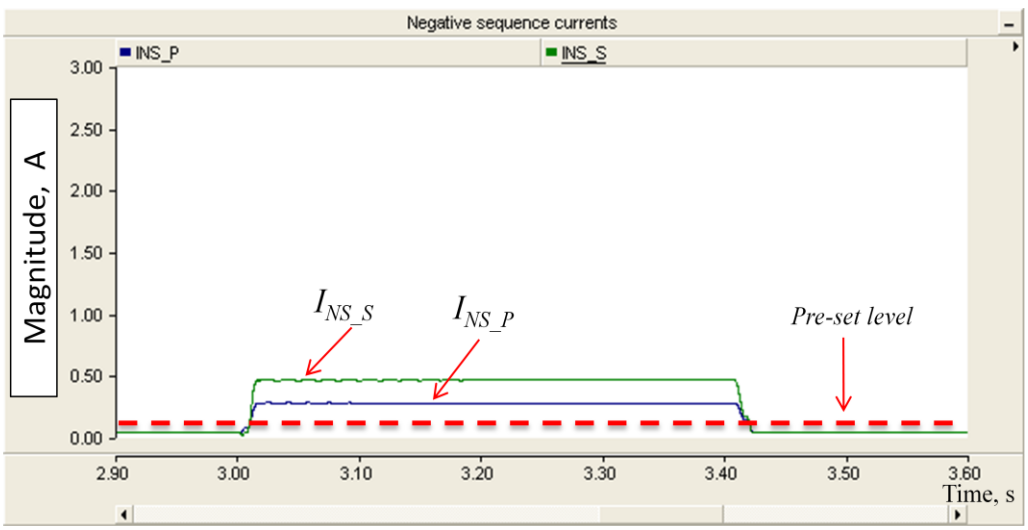


Figure B.3 – Negative sequence current magnitudes for **1%** shorted turns on secondary (Δ-Y)

Figures B.4 - B.6 show the relative phase angle between two phasors of negative sequence currents during an internal turn-to-turn fault, which represent the respective contribution. As it can be seen from Figures B4 - B6, Δ-Y connection of three phase power transformer introduces a 30º phase shift between the primary and the secondary windings.

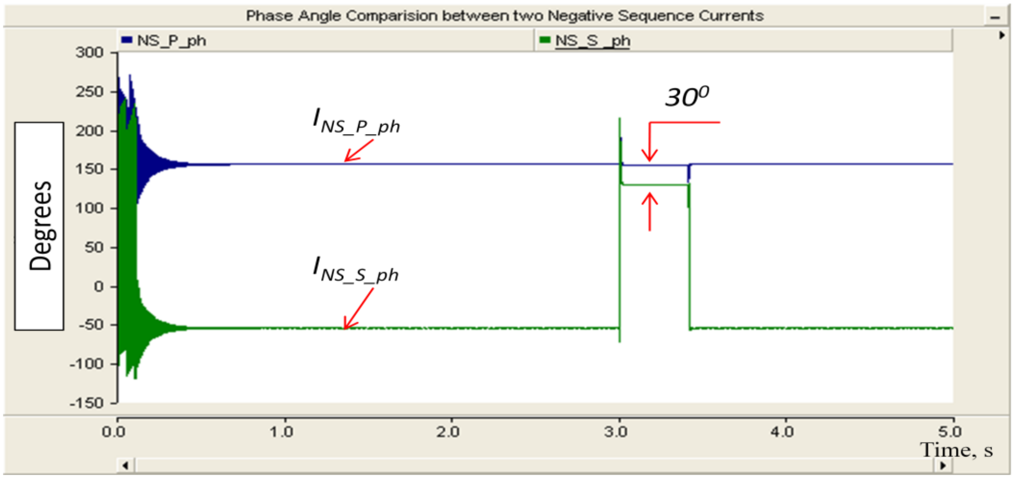


Figure B.4 – Phase angle comparison between two negative sequence currents for **5%** shorted turns on secondary (Δ-Y) with 30º phase shift

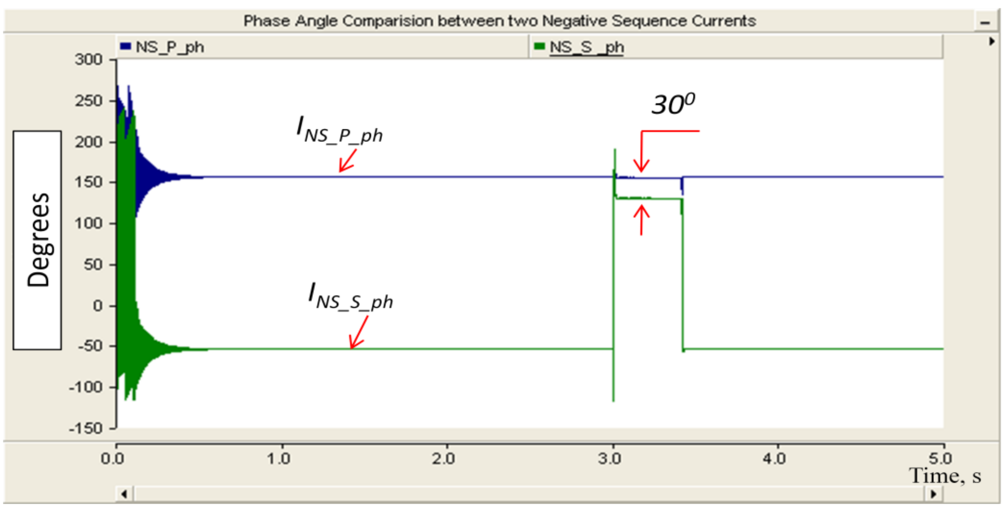


Figure B.5 – Phase angle comparison between two negative sequence currents for **3%** shorted turns on secondary (Δ-Y) with 30º phase shift

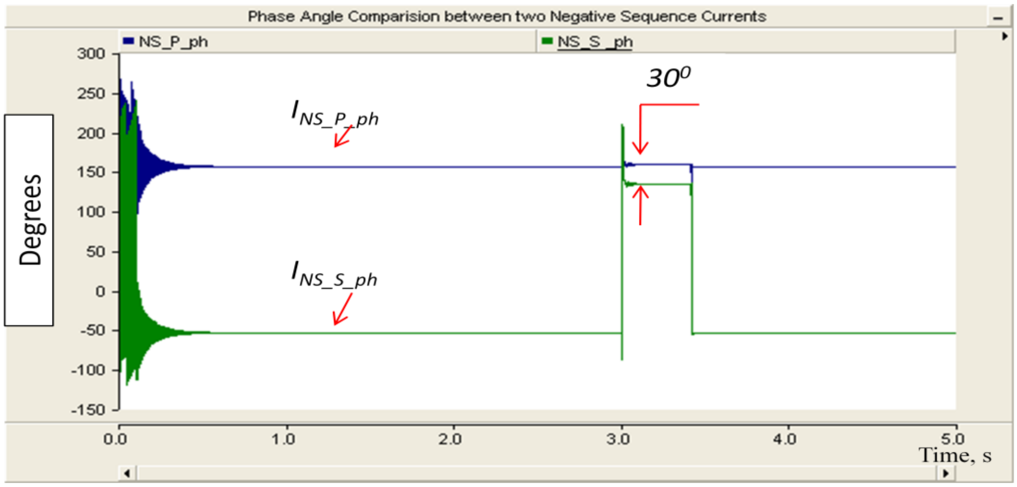


Figure B.6 – Phase angle comparison between two negative sequence currents for **1%** shorted turns on secondary (Δ-Y) with 30º phase shift

However, the comparison between the negative sequence currents on the primary and secondary sides of the power transformer is valid for non-zero phase displacement transformers. If the phase displacement of the transformer differs from zero degrees then the phase shift has to be compensated in order to use this protection method. A 30º phase shift between the primary and the secondary winding of the power transformer is compensated and shown in Figures B7 - B9.

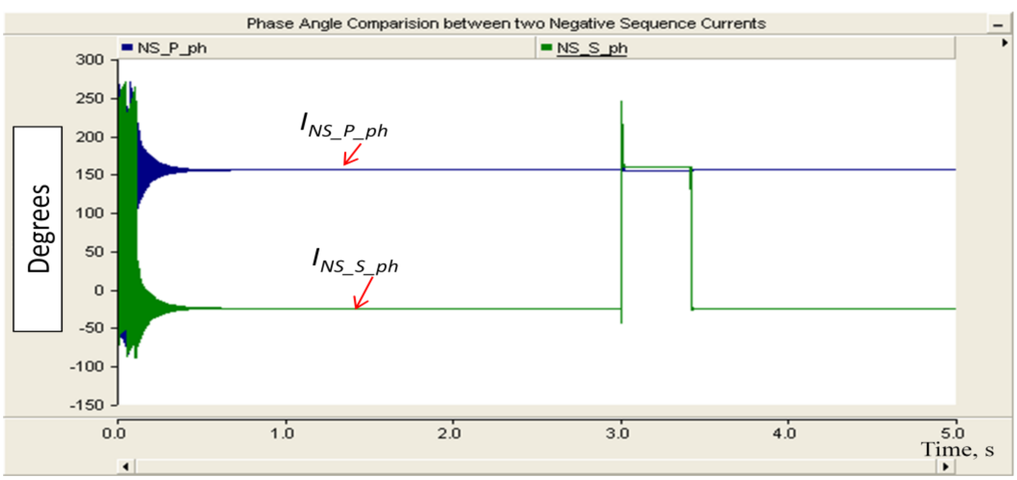


Figure B.7 – Phase angle comparison between two negative sequence currents for **5%** shorted turns on secondary (Δ-Y) without 30º phase shift

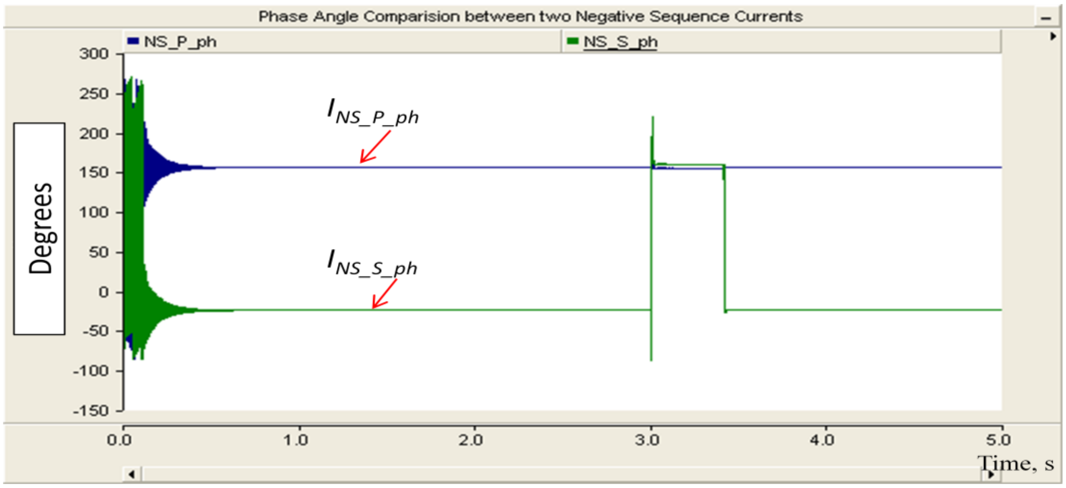


Figure B.8 – Phase angle comparison between two negative sequence currents for **3%** shorted turns on secondary (Δ-Y) without 30º phase shift

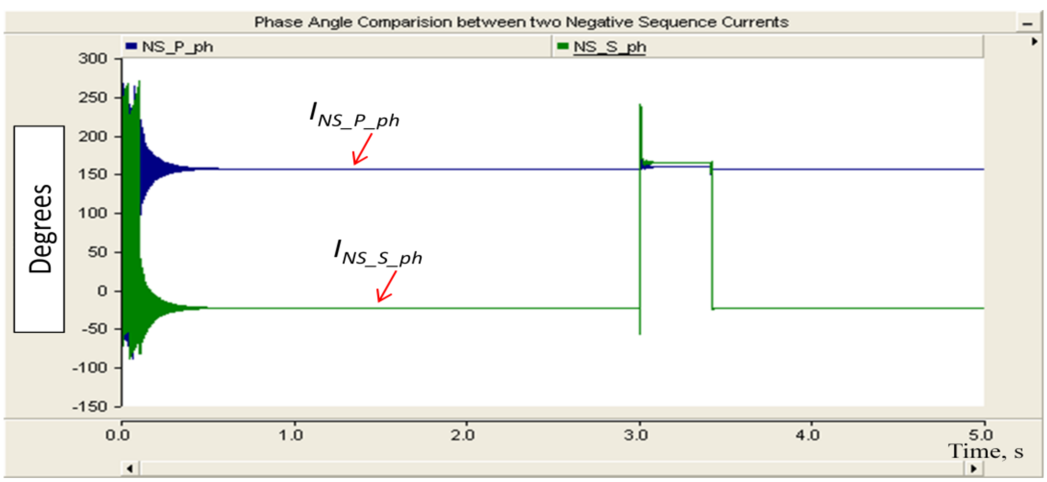


Figure B.9 – Phase angle comparison between two negative sequence currents for **1%** shorted turns on secondary (Δ-Y) without 30º phase shift

When a 30º phase shift between the primary and the secondary winding of the power transformer is compensated, the trip signal from the proposed relay is activated within 1 cycle.